Exploring Ocean Change

BIOACID – Biological Impacts of Ocean Acidification

BIOACID

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A changing ocean

By taking up carbon dioxide from the atmosphere, the ocean slows down global climate change. But when absorbed by seawater, the greenhouse gas triggers chemical reactions, causing the ocean to become more acidic. The German research network BIOACID has investigated the effects of ocean acidification on marine life and its consequences for society and economy.

Photo: Maike Nicolai, GEOMAR

Ocean acidification: addressing the other carbon dioxide problem

"The other carbon dioxide problem", "the evil twin of global warming", or part of a "deadly trio", together with increasing temperatures and loss of oxygen: Many names have been coined to describe the problem of ocean acidification – a change in the ocean chemistry that occurs when carbon dioxide (CO_2) from the atmosphere dissolves in seawater. On the one hand, the ocean's CO_2 uptake slows down global climate change. On the other, this absorption affects the life and material cycles of the ocean – and all those who depend on it.

Between 2009 and 2017, the German research network BIOACID (Biological Impacts of Ocean Acidification) investigated how different marine species respond to ocean acidification, how these reactions impact the food web as well as material cycles and energy turnover in the ocean, and what consequences these changes have for economy and society. More than 250 members of 20 German research institutes, representing a broad range of marine science disciplines, participated in the project coordinated by GEOMAR Helmholtz Centre for Ocean Research Kiel. BIOACID contributed to the scientific discourse on ocean acidification through more than 580 peer-reviewed publications. Throughout three funding phases, the German Ministry of Education and Research supported the project with a total of 22 million Euros.

As a gigantic carbon sink, the ocean has taken up about a third of the carbon dioxide released into the atmosphere by human activities. As a consequence, the average pH at the ocean surface has dropped from 8.2 to 8.1. This tiny step on the logarithmic pH scale translates into a 30 per cent increase in acidity. At the same time, the ocean absorbs more than 90 per cent of the heat that is generated by the greenhouse effect.

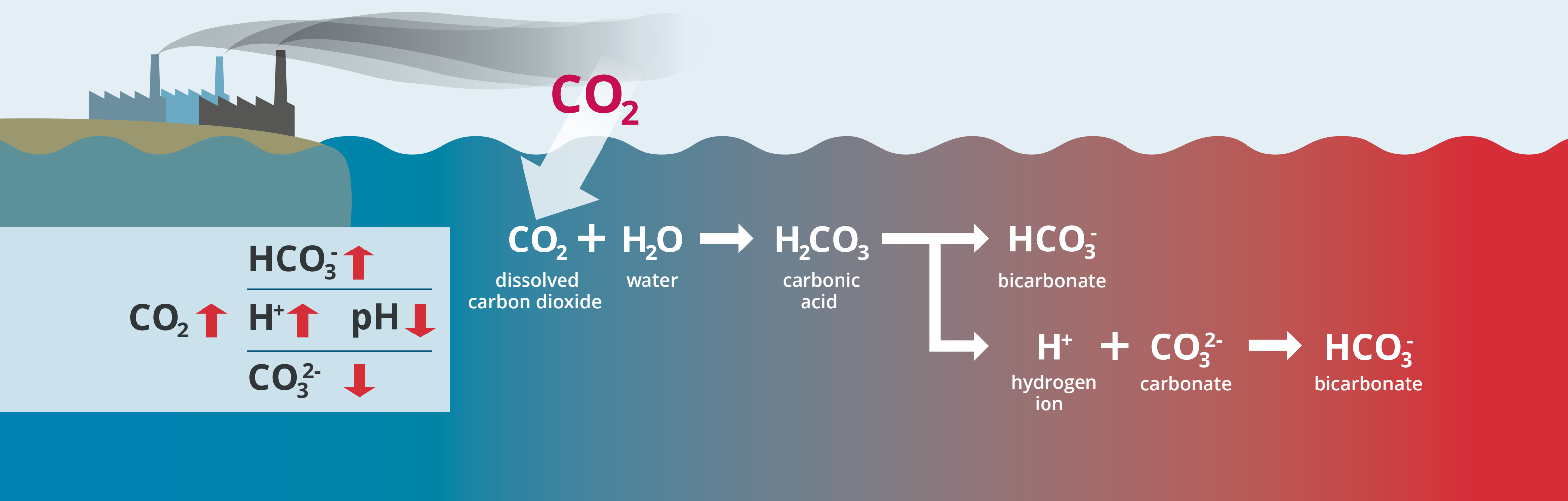
Ocean services under threat

A variety of studies and analyses suggest that ocean acidification and warming affect important services the ocean provides to ecosystems and humankind. This includes the regulation of the Earth's climate, food provision, recreation as well as biodiversity as a condition for intact and functioning ecosystems. This brochure summarises BIOACID results related to these ecosystem services for political decision-making. It reflects not just a focus on human interests, but also respect for the diversity of marine life. Both perspectives make a strong case for limiting climate change.

For the process of ocean acidification, two chemical reactions are particularly important: When carbon dioxide dissolves in seawater, carbonic acid is formed. Hydrogen ions and bicarbonate are released. Part of the hydrogen ions reacts with carbonate to produce bicarbonate.

Calcifying organisms such as mussels, corals or certain plankton species use carbonate to build their shells and skeletons. The more carbonate is lost due to the chemical reactions in the seawater, the more difficult calcification becomes.

Graphic: Christoph Kersten / Rita Erven, GEOMAR



Reaching the Paris climate target

As science gained valuable insights into the effects of climate change on the ocean, it has become possible to predict the direction of many alterations within the complex and dynamic system. But it has also become apparent how difficult it is to form a clear picture. There is no doubt that elemental cycles and marine communities will change and that these changes will impair ecosystem services provided by them. But science is not yet able to assess the exact extent of the risks.

According the precautionary principle – a guideline for German, European and international environmental policies – urgent actions need to be taken to avoid or minimise these risks. The later development towards low-emission and sustainable lifestyles and economies sets off, the larger the effort for adaptation and compensation of irreparable damage becomes.

The Paris Agreement represents an important step in the fight against climate change: In December 2015, the members of the United Nations Framework Convention on Climate Change (UNFCCC) jointly decided to limit human-induced global warming to well below 2, if not 1.5 degrees Celsius. To prevent temperatures from rising by more than 1.5 degrees compared to pre-industrial times, the carbon dioxide concentration in the atmosphere would have to stay below 430 parts per million (ppm). But even for values between 1.5 and 2 degrees, global emissions need to drop to zero very soon. In addition, increasing amounts of the carbon dioxide emitted already need to be removed from the atmosphere and captured safely. Sustainability can only be achieved if society, businesses and politics act together. The reduction of emissions will also keep ocean acidification and risks related to it in bounds. BIOACID is contributing important knowledge to this process.

Ocean acidification and warming are able to affect organisms directly and amplify or attenuate each other's effects. Reactions of individual species also impact other parts of the food web as well as marine communities indirectly. Ultimately, the interaction of effects even has consequences for important ecosystem services such as the uptake and storage of carbon dioxide, food provision from fisheries or the recreational and cultural values of the ocean. *Graphic: Rita Erven, GEOMAR*

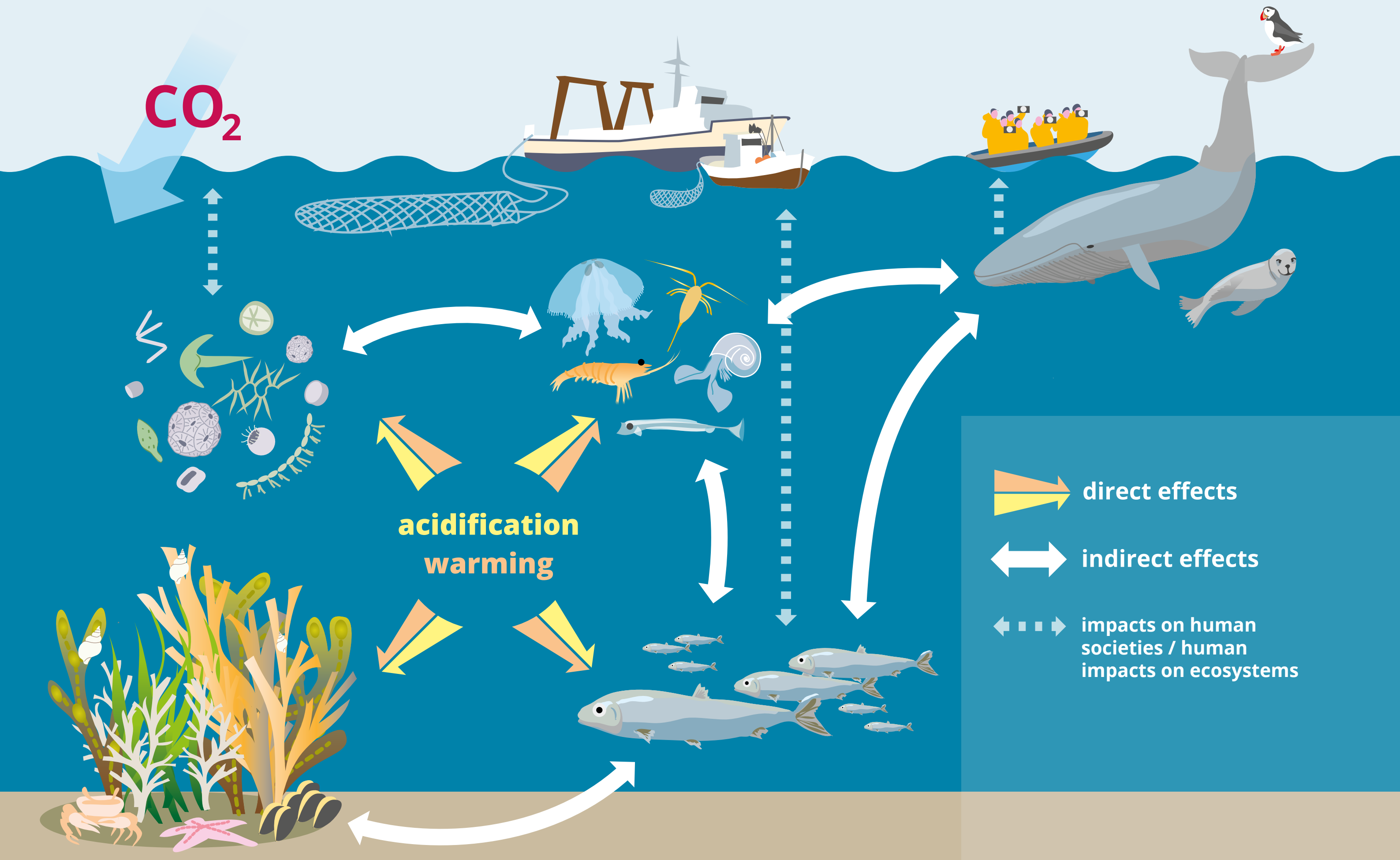


Photo: Maike Nicolai, GEOMAR

Important BIOACID results

- Many organisms are able to withstand ocean acidification, but may lose this ability if also exposed to other stressors such as warming, excess nutrients, loss of oxygen, reduced salinity or pollution.
- A reduction of regional stress such as nutrient runoff or the loss of oxygen can mitigate the impact of global stressors like ocean acidification and warming.
- In a natural community, the impact of stressors on a species can be amplified or diminished by associated shifts in biotic interactions such as competition, predation or parasitism.
- Even small alterations at the base of the food web can have knock-on effects for higher trophic levels.
- Marine life is able to adapt to ocean change through evolution and can partly compensate for negative effects. However, since ocean acidification happens extremely fast compared to natural processes, only organisms with short generation times, such as microorganisms, are able to keep up.
- About half the tropical coral reefs can be preserved if carbon dioxide emissions are limited to concentrations that keep global warming below 1.2 degrees Celsius. However, additional risks posed by ocean acidification are not included in this forecast.
- Ocean acidification reduces the ocean's ability to store carbon.
- Changes in the ocean carbonate system impact the acid-base balance in marine organisms. This can negatively affect key processes such as calcification.
- Climate change alters the availability of prey for fish and as a consequence may affect their growth and reproduction.
- Ocean acidification and warming reduce the survival rates of early life stages of some fish species. This will likely reduce recruitment of fish stocks and ultimately fisheries yields.
- The distribution and abundance of fish species will change. This will have a significant impact on economic activities such as small-scale coastal fisheries and tourism.
- It is crucial to consider ocean acidification and warming in the management of fish stocks and marine areas.
- Following the precautionary principle is the best way to act when considering potential risks to the environment and humankind, including future generations. Even if the extent of possible risks is not fully understood, precautionary measures need to be taken in order to avoid or reduce the harm.
- A more sustainable lifestyle and economy require an interaction between society, businesses and politics. Political frameworks should regulate the phase-out of fossil fuels. It is crucial for every one of us reconsider concepts of normality and adjust behaviour in everyday life.

www.oceanacidification.de/introduction

Life in all its colour

Seawater constitutes about 90 per cent of the habitable space on Earth. Yet less than five per cent of the ocean realm have been explored. Many marine plants and animals are still waiting to be discovered. Thanks to its biodiversity, the ocean performs many important functions and safeguards human wellbeing.

Photo: Solvin Zankl

Planet ocean: the realm of biodiversity

From tiny single-celled organisms to gigantic marine mammals, the ocean is home to a large variety of species – with vast numbers still waiting to be discovered. However, the diversity of plants and animals on land and at sea was even greater before humankind made its appearance. Since the dawn of the anthropocene, we humans have brought about tremendous change to life on Earth. We do not yet fully understand what kind of repercussions the environmental changes caused by our lifestyles will have. But we do know they will eventually affect us directly. Therefore, it is crucially important to keep our impact on nature within bounds.

Seawater covers two thirds of our planet and constitutes about 90 per cent of the habitable space on Earth. But so far, we have only explored less than five per cent of the ocean realm. The Census of Marine Life, an international, ten year initiative to assess the biodiversity of the ocean, discovered more than 6000 new marine species. And still the participants in this project are not even able to estimate how many species live in coastal areas, the regions we claim to know best. Their approximations vary from around 180,000 to more than 10 million species.

Tropical reefs: treasure-troves of biodiversity

Tropical coral reefs give us an idea of the diversity that marine life is able to unfold in one single location. They cover just one per cent of the ocean, but are home to a quarter of all marine species. One square metre of these treasure-troves of biodiversity hosts around 1000 different species.

Warming increases the risk of coral bleaching from which organisms find it hard to recover. According to model calculations, temperatures cannot be allowed to rise by more than 1.2 degrees Celsius if at least half the reefs are to survive. However, this prognosis does not take into account the additional risks posed by ocean acidification.

Stony corals, which form the basis of each colourful reef, grow their solid skeletons from aragonite, the more soluble form of calcium carbonate. In more acidified water, they grow more slowly – under extreme conditions more slowly than the reef erodes. In addition, their skeletons remain more sensitive and thus more susceptible to storms or to organisms that burrow inside the coral or attack its calcium carbonate structure. Because some coral species are better equipped to cope with environmental changes, climate change may reduce the biodiversity of the reefs.

Diversity ensures important functions

Biodiversity, the diversity in species, genetic material and biological communities, is a basic requirement for ecosystem functioning and ultimately even human wellbeing. Only if the various organisms within the marine ecosystem fulfil their roles, can the ocean maintain its functionality and productivity. The ocean regulates our climate and mitigates the effects of climate change, supplies us with food, provides us with inspiration and recreation and it shapes cultural identities. A loss of species can pose a substantial risk for ecosystems as well as the goods and services they provide.

Goods, services and adaptability at risk

The greater the species diversity in a marine community is, the greater its ability to adapt to changes – simply because internal functions and interactions are shared by several types or organisms.

On the other hand, systems formed by only a few species or those strongly relying on certain key players are especially vulnerable. This is why marine life in the Arctic and Antarctic requires special protection.

www.oceanacidification.de/biodiversity

Cold-water coral reef in Norway. Photo: JAGO Team, GEOMAR

Case study

Is there hope for *Lophelia pertusa*?

The world of *Lophelia pertusa* is chilly and dark – but stunningly colourful. Unlike tropical corals, these beauties of the cold are not fed by photosynthesising algae, but catch plankton that drifts by. Because they do not depend on light to thrive, they can exist in ocean depths of hundreds or even thousands of metres.

As a reef engineer, *Lophelia pertusa* forms solid branches that can be white as snow, orange or rose. Yellow sponges and pink "bubblegum corals" stand up between them, often crowded with brittle stars and basket stars. Nestled in the thicket, clams filter food from the water. Crabs and shrimps crawl through this bustle, while fish circle above it. *Lophelia* reefs are teeming with life. They are as impressive as their tropical counterparts and can be found all around the globe.

Because they build their skeletons from aragonite, a highly soluble form of calcium carbonate, cold-water corals such as *Lophelia pertusa* are considered particularly threatened by ocean acidification. Therefore, BIOACID scientists exposed living *Lophelia* corals to simulations of future carbon dioxide concentrations and water temperatures in their laboratories. Under more acidified conditions and an unchanged temperature, the growth rates of the corals decreased. An elevated temperature alone increased growth rates. When acidification was combined with elevated temperature, the corals grew at similar rates as under today's conditions. Thus, in combination the effects of the two different factors compensated each other.

Is this a sign of hope? Researchers are convinced that the overall reaction of the corals strongly depends on the extent at which the ocean acidifies and on the water temperatures the corals experience in the future. *Lophelia pertusa* might only benefit from rising temperatures as long as they remain within the limits this species is currently experiencing within its distribution range. In some regions, however, they are already at their temperature limit. If temperatures continue to rise, warming could amplify the negative effect of ocean acidification instead of compensate it.

Another cause for concern is the fact that only living corals may be able to resist changing conditions. Dead *Lophelia* branches are not protected by organic tissue and might therefore corrode more easily in acidifying waters. But these parts provide the foundation of today's reefs that are so astonishingly rich in species. Further experiments both at the laboratory and in the field will show how flexible *Lophelia pertusa* responds to environmental changes in its natural habitat and where there are limits to its acclimatisation potential. But to definitely preserve the magnificent oases of biodiversity founded by *Lophelia pertusa*, effects of global climate change need to be minimised even now – while science continues to investigate this complex marine ecosystem.

www.oceanacidification.de/case-study-lophelia

Bladderwrack in the Baltic Sea.
Photo: Uli Kunz, Submaris

Case study

Ecosystem engineer under multiple stress

On the rocky shores of the Baltic Sea, the bladderwrack *Fucus vesiculosus* provides a perfect base layer for diverse ecosystems. By colonizing pebbles and rocks along the coasts of the inland sea, bladderwrack creates a home and shelter for small crustaceans, crabs, mussels, sea snails and slugs, algae and even fish. Since the young and brackish Baltic Sea is less rich in species than other marine environments, this ecosystem relies on just a few key players – such as *Fucus vesiculosus*.

Bladderwrack consumes a substantial part of the nutrients present in the water and contributes significantly to the production of organic matter. In doing so, it drives the Baltic's biogeochemical cycles. Species interactions within the *Fucus* community are fine-tuned to keep the system running. If any of its parts were affected by climate change, this would have knock-on effects on both the system and the services it provides to humans.

BIOACID scientists investigated the impact of shifting environmental factors such as an increase in carbon dioxide concentrations, warming and eutrophication – nutrient enrichment – on *Fucus* communities. They transferred the seaweed together with its associated partners such as smaller species of epiphytes – algae that grow on the *Fucus* – grazers like tiny crustaceans and periwinkles as well as mussels into large tanks. In a series of seasonal experiments, they exposed the communities to combinations of present and simulated future seawater temperatures and carbon dioxide concentrations. In addition, an increase in nutrient supply was tested.

The results highlight the combined and seasonal effects of the environmental factors. At current water temperatures, an increase in ocean acidification has almost no effect. But warming can become severely stressful – even more so in combination with increasing concentrations of nutrients and in some cases, of carbon dioxide. Particularly during the summer months, biological interactions within the *Fucus* community can be disrupted: Elevated temperatures weaken the Fucus' chemical defence against the epiphytic algae, whereas the algae themselves benefit from warming, nutrient enrichment and carbon dioxide. The grazers that naturally feed on the epiphytic algae die from high summer temperatures. Ultimately, the bloom of epiphytic algae released from grazing that is triggered by warming in summer suffocates the foundation species *Fucus*. The changes in species interactions influence the overall impact of climate change in marine communities.

Eutrophication is one of the oldest environmental problems in the marine biosphere. The Baltic Sea turned eutrophic – or rich in nutrients – in the 1960s and so far, European water management directives have not fully achieved their objective of a good chemical and ecological status. The results of the experiment highlight that local environmental factors such as eutrophication can amplify the effects of global influences such as rising temperatures. Minimizing local stressors might therefore help key species such as *Fucus vesiculosus* in the Baltic Sea to deal better with with the effects of global climate change and to maintain their important ecosystem services.

www.oceanacidification.de/case-study-fucus

Phytoplankton bloom in the Barents Sea, seen from space.
Photo: NASA, Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC

Climate regulation – and much more

By absorbing carbon dioxide from the atmosphere, the ocean mitigates global warming. This invaluable service is based on chemical and biological processes in the seawater. The cycling of elements also secures many other important ecosystem services. Climate change may disturb their balance.

Life-giving elemental cycles

Carbon, nitrogen and phosphorus: three interacting elemental cycles are essential for life in the ocean. The most important of them is the carbon cycle which also plays a key role in the climate system. Other ocean ecosystem services will be affected by changes in the cycling and exchange of elements as well.

By absorbing approximately 30 per cent of the human-induced carbon dioxide (CO_2) emitted every year, the ocean slows down the increase of the greenhouse gas in the atmosphere and thereby mitigates global warming. But the more carbon dioxide is dissolved in seawater, the lower the ocean's buffer capacity becomes, limiting its ability to take up more. Warming further increases the problem: with rising temperatures, seawater holds less and less CO_2.

The biological carbon pump

Apart from chemical reactions, biological processes control the ocean's CO_2 uptake via the so-called biological carbon pump. In the surface layer, phytoplankton uses carbon dioxide and sunlight to produce organic matter. Some of these particles sink towards deeper layers and are degraded in the ocean interior. In this way, the biological pump tends to lower the carbon dioxide concentration at the surface of the ocean and thus propels the uptake from the atmosphere.

Ocean acidification and rising temperatures lower the efficiency of the biological carbon pump. Surface layer warming increases stratification of the water column. This reduces the nutrient supply into the sunlit upper layer. A decrease in nutrients leads to less organic matter produced at the surface, reducing the amount of carbon transported to the deep.

Ocean acidification weakens the pump

Ocean acidification has been found to cause a shift in the phytoplankton community towards smaller organisms. Since smaller plankton sinks more slowly, the pumping diminishes. In addition, it also becomes harder for calcifying plankton to produce calcium carbonate structures in a more acidified ocean. For example, the single-celled alga *Emiliania huxleyi* wraps itself with chalky platelets. These particles serve as ballast and accelerate the transport of organic matter towards the deep ocean. Hence, less production of calcium carbonate can weaken the biological pump.

These changes to how carbon sinks to the ocean depths will be partially compensated by the increased fluidity of warmer surface waters which make particles sink faster. The complex interaction of these processes makes it extremely difficult to estimate their ultimate effects on the biological carbon pump.

The nitrogen and the phosphorus cycles

Apart from the cycling of carbon, two other nurient cycles need to be in balance to ensure the ocean system functions. The nitrogen and the phosphorus cycles sustain marine life and these will be affected by climate change as well. Nitrogen gas, not accessible to phytoplankton, is fixed by specialised organisms in warm surface waters and made available for the food web. Ocean acidification boosts this important nitrogen source. This could benefit the production of organic matter and hence CO_2 pumping unless limited supplies of other nutrients hamper this effect. At the seafloor, where oxygen is sparse, microbes process oxygenated forms of nitrogen, transforming them back to nitrogen gas which is lost to the atmosphere. As the ocean's oxygen levels decline, the loss of bioavailable nitrogen accelerates, while the release of phosphorus from deep sea sediments increases. Only if the elemental cycles remain roughly in balance, however, will the ocean's productivity be sustained in the future.

Combined, ocean acidification and warming are perturbing marine elemental cycles. In addition to slowing down CO_2 uptake, this is bound to affect life-sustaining fluxes of essential nutrients, impacting ocean productivity, marine food webs and the services they provide.

www.oceanacidification.de/carbonsink

Emiliania huxleyi. Photo: Kai Lohbeck, GEOMAR

Case study

What's next, *Emiliania huxleyi*?

The single-celled calcifying phytoplankton species *Emiliania huxleyi* produces a considerable amount of biomass and calcium carbonate in the ocean, supports the uptake of carbon dioxide at the surface and releases the climate-cooling gas dimethyl sulphide (DMS). It is almost impossible to imagine the marine elemental cycle without the tiny all-rounder. But this is exactly what scientists expect based on laboratory and field experiments. A downturn of the world's most abundant and most productive calcifying organism would have a severe impact on the climate system.

When isolated and exposed to ocean acidification in controlled laboratory experiments, growth and calcification rates of the planktonic alga were only slightly reduced. To some extent, it was even able to counteract the negative effects of ocean acidification through evolutionary adaptation.

But in a KOSMOS mesocosm field experiment investigating its response to ocean acidification in its natural environment, the organism was not able maintain its population size. It failed to form the extensive blooms which it normally does throughout the global ocean.

Emiliania's downfall started well before the bloom period. A reduction in cell growth due to ocean acidification as small as previously observed at the laboratory, caused the population size to gradually decline during the pre-bloom phase. When it was time for *Emiliania* to start bloom formation, there were so few cells left in the plankton community that it could not outgrow its competitors anymore.

Single-celled calcifying phytoplankton such as *Emiliania huxleyi* are also called coccolithophores because of the coccoliths or calcareous plates in which they wrap their cells. Coccolithophores have existed in the world's ocean in many shapes over the past 200 million years. But now their survival seems to be dependent on the trade-off between the energetic costs for calcification under more acidified conditions and the benefit of the calcareous shells.

Researchers assume that the coccoliths serve as protection against predators. But the platelets cannot save the microscopic algae from the threat of climate change. On the contrary, creating this armour might require too much energy for them to survive and maintain their important function for our global climate.

www.oceanacidification.de/case-study-emiliania

Ethical aspects

Fishers in the Senegal.
Photo: Clément Tarif, Greenpeace

Ocean acidification is a creeping threat to the global ocean and life therein. Caused by human activity, this change in seawater chemistry will impact the future of the rich marine biodiversity and important ecosystem services for humans. Because many scientific uncertainties still remain despite large research efforts, the precautionary principle should be applied. With respect to ocean acidification and its effects on the ocean, responsibility needs to be taken for what future generations will encounter.

In environmental ethics, there is an understanding that the current human generation should act against further ocean acidification and, if possible, tackle its impacts. One of the United Nations' Sustainable Development Goals is to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" (SDG 14). A target of these global goals is to "minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels". The principle of minimising losses needs to be specified with precise targets. In particular, greenhouse gas emissions, the main causes for ocean acidification need to be addressed. Climate protection and ocean protection correlate closely with each other in this respect.

The rationale for fulfilling this sustainability objective should be that it benefits all life on Earth. The most common arguments derive from an anthropocentric perspective. It is for our own long-term wellbeing and in accordance with human values to preserve the ocean as we know and cherish it. This also applies to non-economic values such as the beauty of nature, recreation and a sense for the "greatness" of the ocean. Biocentric or ecocentric approaches that recognize an inherent or intrinsic moral value for living beings or ecosystems would postulate even stronger needs to prevent the ocean from acidification.

Assessing risks and identifying reasons for concern always means making a value judgement about which damage or losses are at stake and need to be prevented. A methodological basis for such environmental ethical judgements about ocean acidification is to assess in which way it affects marine ecosystem services that humans benefit from.

The ecosystem service approach, however, is anthropocentric and abstains from answering the question of a possible intrinsic value of nature's creatures. It differentiates between provisioning, regulating and cultural services. Provisioning services like seafood production and regulating services like carbon sequestration are easy to comprehend and to accept as important values.

The value of cultural services for human wellbeing is often underestimated because these are difficult to quantify or to monetise. "Deep" anthropocentric environmental ethics argue that these values are good reasons for an ambitious conservation of nature as well as the ocean.

For example, the presence of a coral reef may shape the cultural identity, traditions and livelihood of a community for generations and at the same time have intense aesthetic and sentimental value to many other people. The loss of these reefs would not only be directly felt by the local community, or others who have sentimental values attached to the reef. Future generations would also be affected negatively.

The problem of ocean acidification – together with other problems – forces us to discard the last big illusion of infinity of nature. Humans have the power to profoundly alter even the ocean. By overcoming this illusion, we must accept our responsibility for the future ocean. Welcome to the anthropocene.

Frederike Böhm, Prof. Konrad Ott | Philosophy and Ethics of the Environment, Kiel University

www.oceanacidification.de/ethics

Foodweb changes

Fish and seafood feed people around the globe. Fisheries are an important source of income in many regions. But what does the future hold? In the Arctic, people already observe how ocean change alters marine food webs and how this influences their economy and culture.

Photo: Fredrik Jutfelt

How long will we be able to eat fish?

Around the world, people depend on fish and seafood for food security and on fisheries to earn their liveli-hoods. In some countries, fish are the most important source of protein. Fish and shellfish are considered as traditional or gourmet food not just in coastal areas. Small-scale fisheries can shape identities in indigenous cultures. A number of national economies highly depend on profits from fish export.
However, more than a third of global fish stocks are rated as overfished. Establishing and safeguarding a sustainable use of these valuable resources is a major challenge for international policies.

Climate change increases pressure on exploited fish stocks. Ocean acidification and warming both put economically important species under severe stress and may considerably decrease their populations. Scientists argue that reducing catch rates might prevent stocks from collapsing and allow fish populations to cope with environmental changes.

Less energy for body functions

Laboratory and field experiments have revealed how ocean acidification and warming might hamper the development of fish and stock recruitment. Elevated temperatures may increase the energy demand of fish. Studies showed that prey for fish may be less abundant or less nutritious in a warmer and more acidic ocean. As a result, it is not guaranteed that all of the body functions of fish can be fuelled with energy. In some species, increased water temperatures and carbon dioxide concentrations can also impair the development during early life stages. Fish offspring depend on their yolk sac during the first few days after hatching. Size as well as energy content of the yolk sac is influenced by ocean acidification and warming, putting larval fitness at significant risk.

Towards a fairer fisheries management

Based on these results, BIOACID members demonstrated in model calculations that the fate of the most important North Atlantic wild fish stocks in the next 20 to 40 years will depend on technical progress in fishing gear, the demand for fish and the effectiveness of fisheries regulations, at least as much as on the other consequences of human-induced ocean change. The models highlight the urgent need to include direct and indirect effects of climate change in fisheries management strategies to avoid fish population declines. Taking climate change into account in fisheries regulations is crucial for an economically and ecologically viable use of fish stocks in the longer term.

www.oceanacidification.de/fisheries

Fishers on the Baltic Sea, seagulls, fisheries research on board of ALKOR. Photos: Maike Nicolai, GEOMAR



Case study

The Arctic – an early warning system

The Arctic Ocean is already being impacted by the effects of climate change. Like an early warning system, it is exhibiting transformations that other places may undergo in the future.

Air and water temperatures have risen since the end of the 19th century, and the annual mean Arctic sea-ice extent has decreased during recent decades. Because of its still comparably low water temperatures, the ice-free areas of the Arctic Ocean also absorb more carbon dioxide from the atmosphere and acidify more intensely than warmer waters. Already at present, acidification and warming affect organisms throughout the marine food web.

The polar cod *Boreogadus saida* is one of the key players in the Arctic ecosystem. It is preyed upon by larger fish, birds and marine mammals such as seals and whales. Polar cod spend part of their life cycle under the sea ice, feeding on zooplankton which in turn lives on ice algae that can be found directly under the ice. For this reason, a retreat of the sea ice can eventually cause a reduction of polar cod stocks.

As a highly-specialised species, polar cod have adapted to the relatively stable low temperatures and sparse food availability of the Arctic Ocean. According to BIOACID experiments, these fish have difficulties adjusting their metabolism to a warmer environment and cannot cope with a broad range of temperatures. As a consequence, they are forced to retreat to higher latitudes – their habitat shrinks.

Around Svalbard, at the southern range of their distribution, polar cod increasingly face competition with its larger, voracious relative, the Atlantic cod *Gadus morhua*. This species is migrating north due to rising water temperatures. It not only feeds on polar cod and capelin – juvenile Atlantic cod also compete directly with polar cod for food sources.

Ocean acidification will take its toll on both cod species, mostly by further exacerbating negative effects of ocean warming. BIOACID scientists have found that both drivers work synergistically, especially on the most sensitive early life stages of polar cod as well as embryo and larval survival.

At the moment, Atlantic cod still benefit from ocean warming at the northern boundary of its distributional range. But an ecological model which integrates the results from BIOACID experiments finds that early recruitment success of the cod stock in the Barents Sea, a marginal sea of the Arctic Ocean, may be strongly reduced by combined acidification and warming in the second half of the 21st century.

To cope with the challenges of a changing ocean, marine organisms require extra energy. Therefore, scientists are eager to assess changes in food web composition and nutrient availability.

The sea butterfly *Limacina helicina* is an important food source for lots of marine animals, including polar and Atlantic cod. Sea butterflies are tiny swimming snails that carry calcium carbonate shells. Ocean acidification and warming affect their shell growth and metabolism which might reduce their value as prey. Furthermore, field studies suggest that their numbers might decrease. These observations indicate that some important food sources are negatively affected by ocean acidification and warming with consequences for organisms at higher trophic levels.

As polar species are specifically adapted to lead a low-energy lifestyle, they develop comparably slowly and react with less flexibility to changes in their environment. By contrast, species in temperate regions are adapted to a wider range of environmental conditions. From this point of view, polar ecosystems appear to be most susceptible to even subtle environmental changes brought about by climate change.

www.oceanacidification.de/case-study-arctic

Fishing boat in the Lofoten.
Photo: Stefan Königstein, University of Bremen

Case study

Eyewitnesses of ocean change

Atlantic cod and haddock stocks are moving northeast, while mackerels are immigrating from the south. Spawning seasons and spawning grounds are shifting. The population size and distribution range of seabirds and marine mammals are changing. Fishers and members of the ocean-related tourism sector in Northern Norway are already noticing these effects of climate change that are transforming their home region. The area belongs to the Barents Sea, a part of the Arctic Ocean that has, up to now, been characterized by a wealth of fish resources and its high-latitude climate. But water temperatures in the Barents Sea are rising substantially, while a comparably high rate of ocean acidification is projected over the course of this century.

For this reason, BIOACID scientists chose the Barents Sea region as their study area for the impacts of global change on human communities that depend on the ocean and their ability to adapt. Coastal small-scale fishers, fisheries associations, coastal tourism entrepreneurs, environmental and indigenous organisations, as well as governmental departments shared their observations, interests and concerns with researchers in interviews and workshops.

Based on this first-hand knowledge, an integrative model was developed and then assessed together with the stakeholders. In this way, it became clear how ocean acidification and warming might alter the marine ecosystem in the Barents Sea, in which ways the changes might affect people and businesses and how they could adapt to the changes.

If fish stocks move from coastal areas to the open sea, traditional small-scale fishers are not able to follow them with their boats. This possibly forces them to make large investments to adapt their gear or to give up their jobs. Sports fishing and whale watching may become too difficult because of the longer distances incurred – or tour operators might have to chose to focus on other aspects of nature or active tourism. On the other hand, larger fishing companies trust the Norwegian fishing quota management to secure their future incomes, and sustainable aquaculture could increasingly become an alternative for food provision.

The Barents Sea study provides an example of the unexpected and often indirect impacts of ecological shifts on different groups in society which may occur under ocean acidification and warming. An improved assessment of ecological interactions as well as increased consideration of user groups with fewer adaptation options would ensure a fairer and more sustainable governance of marine resources and areas.

www.oceanacidification.de/case-study-stakeholders

A place of recreation

Many people spend their holidays at sea. The marine climate and the view of the blue ocean allow them to relax. But rising temperatures and carbon dioxide concentrations, lack of oxygen and excess in nutrients benefit the development of harmful algae.

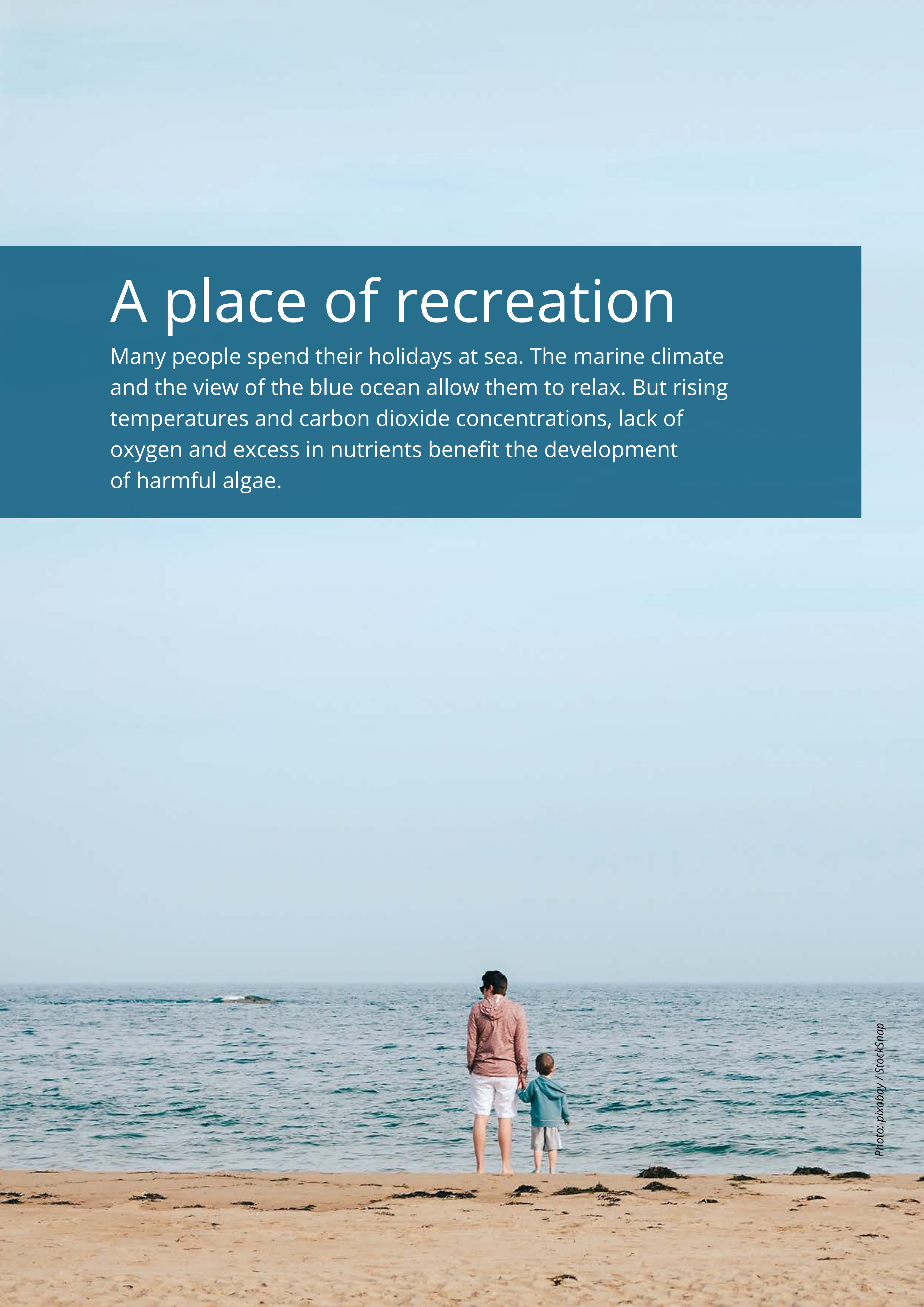


Photo: pixabay / StockSnap

Dolce vita at the Baltic coast?

Warmer water and air temperatures, drier summers, an early spring and a late autumn. On the surface, the effects of climate change might seem to benefit tourism in the Baltic Sea region.

Will the North German coast lend itself to pleasant seaside holidays almost all year long, while temperatures could climb to 40 degrees Celsius in currently popular seaside resorts around the Mediterranean?

It's not that simple. Our seas and beaches will not remain the same in the near future. At high temperatures, the water loses oxygen. In addition, the sea takes up carbon dioxide from the atmosphere – an additional nutrient for photosynthesising algae and sea grass. The rising sea level, combined with storms, storm tides and heavy rainfalls might ruin coastlines if they are not protected properly.

www.oceanacidification.de/recreation

Case study

Cyanobacteria, the killjoys at the beach

Cyanobacteria, also known as "blue green algae" are among the organisms that benefit from ocean change. In the Baltic Sea, the species *Nodularia spumigena* manages perfectly with water temperatures above 16 degrees Celsius and elevated carbon dioxide concentrations – whereas other organisms already reach their limits at less warming.
The microscopic filamentous bacteria produce organic material using nitrogen from the air and the phosphate that is abundant in the Baltic Sea. In summer, they grow in large number and develop so-called blooms. The bacteria can then form patches bigger than 60,000 square kilometres on the water surface. BIOACID experiments suggest that the combination of warming, ocean acidification and oxygen limitation will support the productivity of cyanobacteria.

Beneath the bacterial mats, other organisms have difficulties to survive, as they lack the necessary light for growth. The degradation of dead cycnoabacteria blooms at the seafloor requires more oxygen – which can affect life in an environment that is already poor in oxygen.

Swimming is often prohibited during blue-green algae blooms, because *Nodularia spumigena* releases the toxins microcystin and nodularin from its cells. They can irritate the skin and eyes or cause sickness in humans. The toxins can also harm the livers of smaller marine animals.

www.oceanacidification.de/case-study-cyanobacteria

Cyanobacteria. Photo: Kristin Beck, IOW. Cyanobacteria under the microscope. Photo: Regina Hansen, IOW

Obligations for politics and society

Photo: NASA, Apollo 11

Fossil fuels are the main source of greenhouse gas emissions and air pollution. Both are not only drivers of climate change but also cause ocean acidification. Knowledge of natural scientific facts on sea and climate alone however does not trigger sufficient motivation in society, businesses and politics to reduce their emissions. In the context of BIOACID, this phenomenon has been broadly evaluated in the light of different behavioural science branches. Oftentimes, short-term self-interest stands in the way of taking action. But also, emotional factors such as convenience, habits and the difficulties to experience complex and distant processes like climate change and ocean acidification as urgent issues are relevant. Social transformation towards sustainable lifestyles and economies will only succeed if all stakeholder groups interact. Getting used to new conceptions of normality is of particular importance. The usual emissions-intensive lifestyle in industrialised countries and increasingly in developing countries has to be put on the spot.

Citizens, enterprises and politics must be aware, that the problems will not be solved by just shifting them e.g. to different water bodies when the sea is overfished. Equally, it is not useful to reduce emissions in Europe, when consumption goods produced abroad (including their emissions) will be imported here. Ocean acidification and climate change therefore are feature examples of truly global problems: Purely national strategies will definitely not suffice to solve them.

Starting there, BIOACID research was done to explore options for effective ocean acidification policies. One of those will induce a fast phase-out of fossil fuels, because of their significant role in creating the problem. The most effective mechanism for that is to define clear political steps to eliminate fossil fuels used for power, heating, fuels and industrial use (such as fertiliser) from the market by implementing a mechanism for quantity control. This would mean a drastically reformed EU Emissions Trading Scheme. Different from the current scheme, all sectors would need to be included. Quantity limits need to be set a level that will lead to zero fossil fuels in a maximum of 20 years. This is as much called for by human rights (see below) as it is by Art. 2 of the Paris Climate Agreement, which has been analysed from a legal and political science perspective. The article limits global warming to well below 2 degrees below preindustrial levels. Acting on that, ocean acidification, climate change, but also pollution of air, water and soil and loss of biodiversity would all be addressed.

In general terms, international law of the sea, and nature conservation law also call for preventing the dangers of environmental problems. They can, however, not substitute the approach sketched out above. Liability law and industrial plants law will also not contribute substantial solutions for global environmental problems like ocean acidification and climate change. Even though, concrete damage can occur if fishermen harvest less fish due to ocean acidification. However, these damages cannot be traced back correctly to the individual emitters.

Besides the aforementioned international climate and nature conservation law, human rights – also analysed in the scope of BIOACID – call for effective political measures against global dangers to the environment, such as ocean acidification and climate change. Because human rights also imply the right to the elementary preconditions of freedom such as access to food, water or a stable climate. Protection of marine ecosystems falls at least partially under this category. Because ecosystem services include food supply, absorption of greenhouse gases or hosting biodiversity. These services of the sea, which are necessary for humankind to exist, are endangered by continuous ocean acidification and climate change.

Prof. Dr. Felix Ekardt | Research Unit Sustainability and Climate Policy, Leipzig/Berlin

www.oceanacidification.de/politics

Personal statements

Frederike Böhm | Department of Philosophy, Kiel University

I like to follow the concept "reduce – reuse – recycle" when it comes to consumption: borrowing, sharing or buying second-hand are often good alternatives to purchasing new things, the production of which causes additional carbon dioxide emissions and use resources. Moreover, I can easily live without animal-based foods – another way to reduce greenhouse gas emissions and at the same time reduce the demand for threatened fish stocks. For the future, one of my intentions is to consume less overall and to try harder to avoid waste. That is also a step towards tackling the additional challenge of plastic in the ocean.

Prof. Dr. Hans-Otto Pörtner | Alfred Wegener Institute, Bremerhaven

If you focus on the consequences of climate change in your work as a scientist, it is hard to exclude these aspects from your day-to-day lifestyle. I try to avoid emissions as best I can. Buying clean power or wind gas at my home, using the bike or public transport for regular journeys or driving a car that is nominally powered by wind gas are among present options for people living in Germany. But the number of options is still too limited. This illustrates that the structural transformation of our cities and communities is not happening fast enough to facilitate a daily life for all that follows the rules of sustainability. Maybe politics has not realised yet how urgently we need to reduce our emissions and even extract carbon dioxide from the air in order to reach our long-term climate goals and to avoid dangerous impacts of climate change.

Dr. Stefan Königstein | University of Bremen

It was amazing for me to see how present the issue of climate change is to the people of northern Norway. Whether fishermen, hotel owners or mountain tour suppliers, every person I interviewed was able to contribute to the observation of long-term ecological changes – be it the retreat of the winter snow cover, alterations in precipitation or the changing distrubution of fish, seabirds, trees and reindeer. It was exciting to see that many of these observations are clearly ahead of science – much of it was published much later, or not at all, in the scientific literature. I think we would benefit greatly if we incorporated this knowledge much earlier, even in the conceptual phase of research projects.

Dr. Martina Stiasny | Department of Economics, Kiel University

With my research I am aiming to answer questions with relevance to society and conservation. Ocean and climate protection are some of the most pressing problems of our time. Solutions need to work on many different levels, socially, ecologically and economically. It is therefore imperative to include stakeholders as early as possible and to include their interests without losing sight of the aim of conservation. Because of this I purposefully work with ecologists and economists in order to shape fisheries management sustainably even in times of global change.

Dr. Lena Jakob | Alfred Wegener Institute, Bremerhaven

The message of the Paris Climate Agreement is clear: in 2050 emissions per capita should be limited to less than one ton of carbon dioxide (CO_2) equivalents. Today, the average consumer in Germany emits 11.63 tons of CO_2 equivalents. So what can I do to minimize my carbon footprint? The German Federal Environmental Agency provides a CO_2 calculator (www.co2-rechner.de). Here the factors heating, electricity, mobility, nutrition, consumption and public emissions are considered. I end up with an annual emission of 9.03 tons of CO_2 equivalents. Although this is 22 per cent less than the nationwide average, I am still miles away from a climate-neutral life. My conclusion: without serious political measures, I cannot manage to live a climate-neutral life. But the CO_2 calculator showed me, that I have a large individual scope of action in order to get closer to a climate-neutral life.

www.oceanacidification.de/video-en

Photos: Rolf Wittig, private, Leonard Rokita, Kerstin Rolfes, Maike Nicolai

Sea butterflies (pteropods). Photo: Solvin Zankl

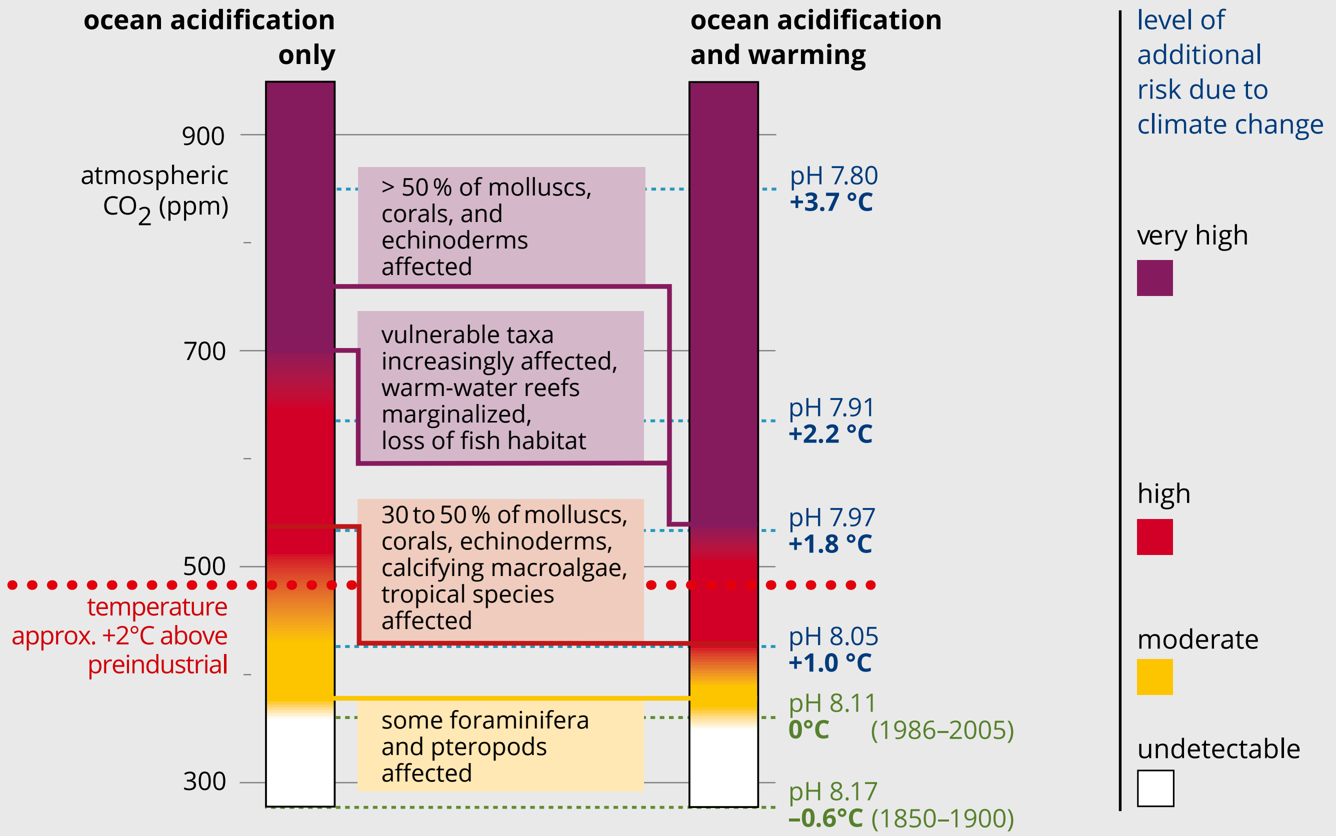
Assessing the risks of ocean acidification

The regular world climate reports compiled by the Intergovernmental Panel on Climate Change (IPCC) form the most reliable basis for political decisions regarding climate change.

For the fifth issue, the IPCC defined five current Reasons for Concern (RFC), eight key risks as well as four risk levels. The “Burning Ember” diagrams – the name refers to the colour gradient – visualise risks related to climate change. The corresponding narrative complements the graph.

BIOACID results are summarised here in line with the IPCC approach in order to facilitate the integration into the upcoming sixth assessment report. Included are also results of a meta-analysis of hundreds of individual studies – including many investigations conducted by the project itself – that has been produced as part of BIOACID. By providing a global perspective on the impacts of ocean acidification and warming, the Burning Ember diagram and the narrative presented here complement the case studies described in this brochure. However, a global picture cannot be compiled without many regional and local findings.

Risk for marine species impacted by ocean acidification only, or additionally by warming extremes



Source: IPCC Synthesis Report 2014; O'Neill et al., 2017; updated here: Mintenbeck and Pörtner, in preparation.

projected pH, temperature for 2081 – 2100
observed pH, temperature

(temperature in °C relative to 1986 – 2005)

Risks of harmful ecosystem effects of ocean acidification are considered moderate around current carbon dioxide (CO_2) levels of about 380 ppm. At these levels, decreasing calcification due to anthropogenic ocean acidification is already observed in some foraminifera and pteropods. In addition, negative impacts on pteropods and oyster cultures along the west coast of North America have been attributed to upwelling of acidified water shifted closer to shore combined with anthropogenic acidification.
Under ocean acidification only (left column, warming excluded), the transition to high risk occurs at a CO_2 level of about 500 ppm, beyond which studies reflect onset of significantly negative effects and high risk in 30 to 50 per cent of extant calcifying taxa (corals, echinoderms, molluscs, calcifying macroalgae; in particular tropical species).
Risks are estimated to be very high with limited capability to adapt beyond about 700 ppm, based on a rising percentage of the calcifying taxa being negatively affected. For the calcifying invertebrate taxa, these conclusions are confirmed by observations at natural analogues (volcanic CO_2 seeps, upwelling systems) and by similar sensitivity distributions among taxa during paleo-periods.

Current knowledge indicates that the combined pressures of ocean warming extremes and acidification lead to a shift in sensitivity thresholds to lower CO_2 concentrations, as seen in corals and crustaceans.
For corals this comes with the risk that ocean acidification will increasingly contribute to the reduction in areal extent of coral ecosystems, already underway as a result of interacting stressors (extreme events, predation, bleaching). Knowledge of the long-term persistence of acidification impacts presently relies on findings in the paleo-records. Therefore, evidence that changes in extant ecosystems will persist is limited, especially for fish (fish seem to be primarily affected by habitat loss due to increasing water temperature). Additionally, knowledge is scarce on compensatory mechanisms and their capacity and associated limits to long-term evolutionary adaptation under ocean acidification and warming.

Updated from: O'Neill et al., 2017, Nature Climate Change, 7, 28–37, doi:10.1038/nclimate3179

www.oceanacidification.de/reasonsforconcern

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