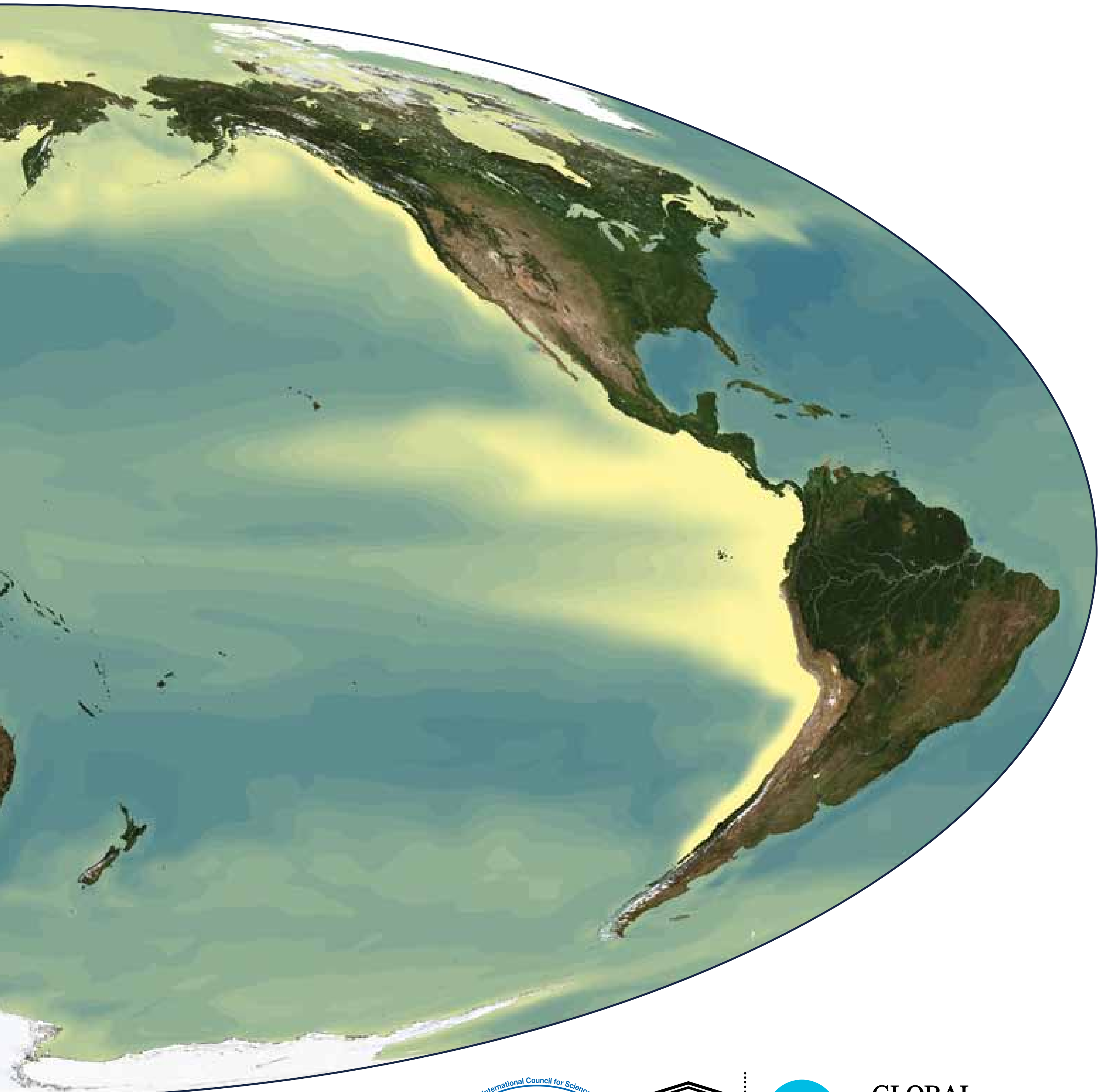
OCEAN ACIDIFICATION

Summary for Policymakers

Third Symposium on the Ocean in a High-CO_2 World



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Ocean Acidification

Ocean acidification research is growing rapidly. The Third Symposium on the Ocean in a High-CO_2 World (Monterey, California, September 2012) convened 540 experts from 37 countries to discuss the results of research into ocean acidification, its impacts on ecosystems, socio-economic consequences and implications for policy. More than twice as many scientists participated in the Monterey symposium compared to the previous symposium four years earlier.

Here we present a summary of the state of knowledge on ocean acidification based on the latest research presented at the symposium and beyond.

Atmospheric carbon dioxide (CO_2) levels are rising as a result of human activities, such as fossil fuel burning, and are increasing the acidity of seawater. This process is known as ocean acidification. Historically, the ocean has absorbed approximately a quarter of all CO_2 released into the atmosphere by humans since the start of the industrial revolution, resulting in a 26% increase in the acidity of the ocean[1].

Ocean acidification causes ecosystems and marine biodiversity to change. It has the potential to affect food security and it limits the capacity of the ocean to absorb CO_2 from human emissions. The economic impact of ocean acidification could be substantial.

Reducing CO_2 emissions is the only way to minimise long-term, large-scale risks.


Katharina Fabricius

Summary of outcomes

During the last 20 years, it has been established that the pH of the world's oceans is decreasing as a result of anthropogenic CO_2 emissions to the atmosphere.

The Third Symposium on the Ocean in a High-CO_2 World built on this knowledge.


Katharina Fabricius

- The ocean continues to acidify at an unprecedented rate in Earth's history. Latest research indicates the rate of change may be faster than at any time in the last 300 million years.
- As ocean acidity increases, its capacity to absorb CO_2 from the atmosphere decreases. This decreases the ocean's role in moderating climate change.
- Species-specific impacts of ocean acidification have been seen in laboratory and field studies on organisms from the poles to the tropics. Many organisms show adverse effects, such as reduced ability to form and maintain shells and skeletons, as well as reduced survival, growth, abundance and larval development. Conversely, evidence indicates that some organisms tolerate ocean acidification and that others, such as some seagrasses, may even thrive.
- Within decades, large parts of the polar oceans will become corrosive to the unprotected shells of calcareous marine organisms.
- Changes in carbonate chemistry of the tropical ocean may hamper or prevent coral reef growth within decades.
- The far-reaching effects of ocean acidification are predicted to impact food webs, biodiversity, aquaculture and hence societies.
- Species differ in their potential to adapt to new environments. Ocean chemistry may be changing too rapidly for many species or populations to adapt through evolution.
- Multiple stressors – ocean acidification, warming, decreases in oceanic oxygen concentrations (deoxygenation), increasing UV-B irradiance due to stratospheric ozone depletion, overfishing, pollution and eutrophication – and their interactions are creating significant challenges for ocean ecosystems.
- We do not fully understand the biogeochemical feedbacks to the climate system that may arise from ocean acidification.
- Predicting how whole ecosystems will change in response to rising CO_2 levels remains challenging. While we know enough to expect changes in marine ecosystems and biodiversity within our lifetimes, we are unable to make reliable, quantitative predictions of socio-economic impacts.
- People who rely on the ocean's ecosystem services are especially vulnerable and may need to adapt or cope with ocean acidification impacts within decades. Shellfish fisheries and aquaculture in some areas may be able to cope by adjusting their management practices to avoid ocean acidification impacts. Tropical coral reef loss will affect tourism, food security and shoreline protection for many of the world's poorest people.

Mitigation and adaptation

Ocean acidification is not explicitly governed by international treaties. United Nations (UN) processes and international and regional conventions are beginning to note ocean acidification (London Convention/Protocol, UN Convention on the Law of the Sea, Convention on Biological Diversity and others). Negotiators to the UN Framework Convention on Climate Change (UNFCCC) have begun to receive regular reports from the scientific community on ocean acidification, and the issue is now covered in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

In June 2012, the UN Conference on Sustainable Development (Rio+20) recognised ocean acidification as a threat to economically and ecologically important ecosystems and human wellbeing.

However, there are still no international mechanisms or adequate funding to deal specifically with mitigation or adaptation to ocean acidification.

Policy considerations

- The primary cause of ocean acidification is the release of atmospheric CO_2 from human activities. The only known realistic mitigation option on a global scale is to limit future atmospheric CO_2 levels.
- Appropriate management of land use and land-use change can enhance uptake of atmospheric CO_2 by vegetation and soils through activities such as restoration of wetlands, planting new forests and reforestation.
- Geoengineering proposals that do not reduce atmospheric CO_2 – for example, methods that focus solely on temperature (such as aerosol backscatter or reduction of greenhouse gases other than CO_2) – will not prevent ocean acidification. Adding alkaline minerals to the ocean would be effective and economically feasible only on a very small scale in coastal regions, and the unintended environmental consequences are largely unknown[2].
- The impacts of other stressors on ocean ecosystems such as higher temperatures and deoxygenation – also associated with increasing CO_2 – will be reduced by limiting increases in CO_2 levels.
- The shellfish aquaculture industry faces significant threats and may benefit from a risk assessment and analysis of mitigation and adaptation strategies. For example, seawater monitoring around shellfish hatcheries can identify when to limit the intake of seawater with a lower pH, hatcheries can be relocated, or managers can select larval stages or strains that are more resilient to ocean acidification for breeding.
- At local levels, the effects of ocean acidification on ecosystem resilience may be constrained by minimising other local stressors[3,4,5] through the following:
    - Developing sustainable fisheries management practices such as regulating catches to reduce overfishing and creating long-term bycatch reduction plans. If implemented and enforced, this type of management has been shown to sustain ecosystem resilience.
    - Adopting sustainable management of habitats, increased coastal protection, reduced sediment loading and application of marine spatial planning.
    - Establishing and maintaining Marine Protected Areas (MPAs) that help manage endangered and highly vulnerable ecosystems to enhance their resilience against multiple environmental stressors[6].
    - Monitoring and regulating localised sources of acidification from runoff and pollutants such as fertilisers.
    - Reducing sulphur dioxide and nitrous oxide emissions from coal-fired power plants and ship exhausts[7] that have significant acidifying effects locally.

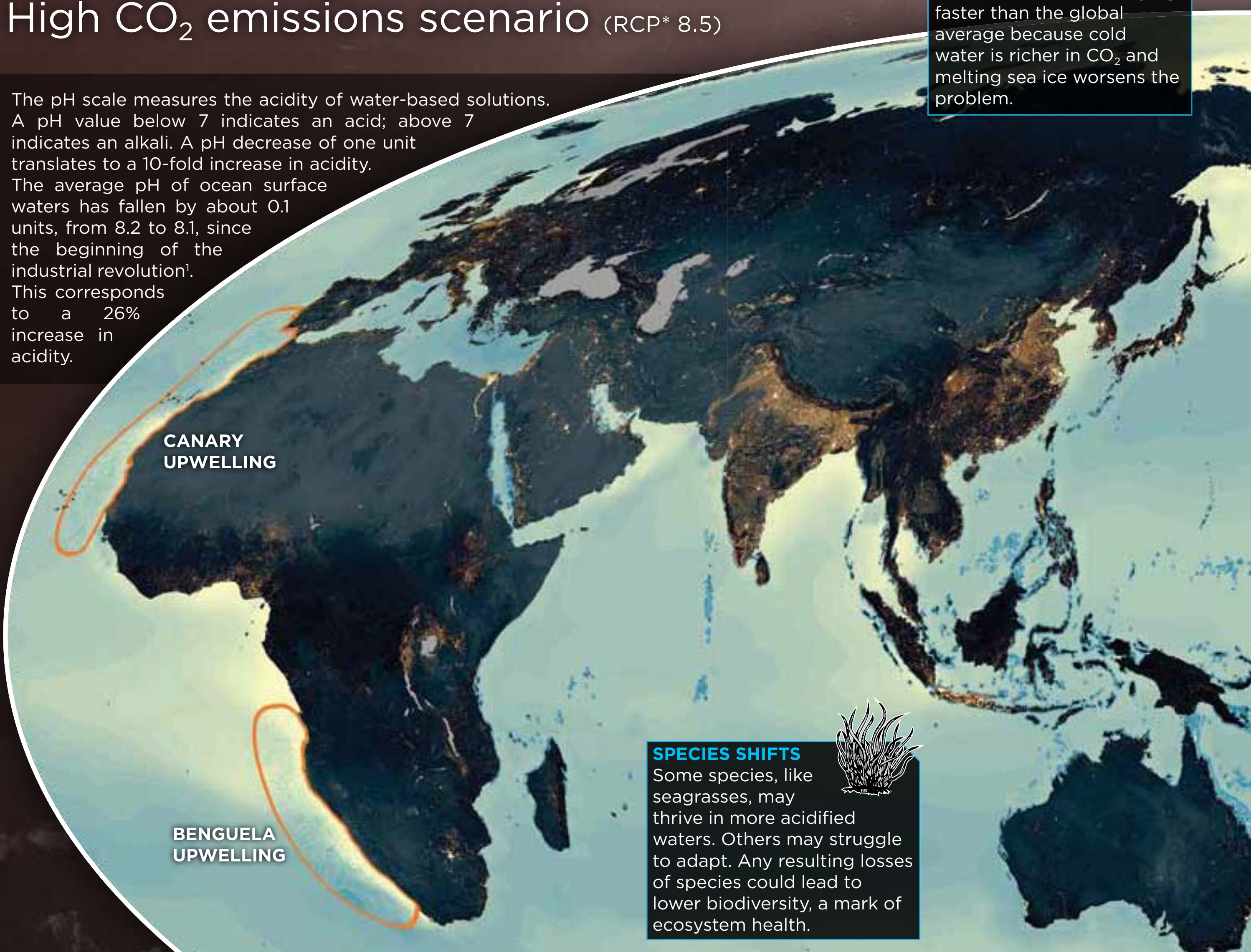
OCEAN ACIDIFICATION

Ocean pH in 2100

High CO_2 emissions scenario (RCP* 8.5)

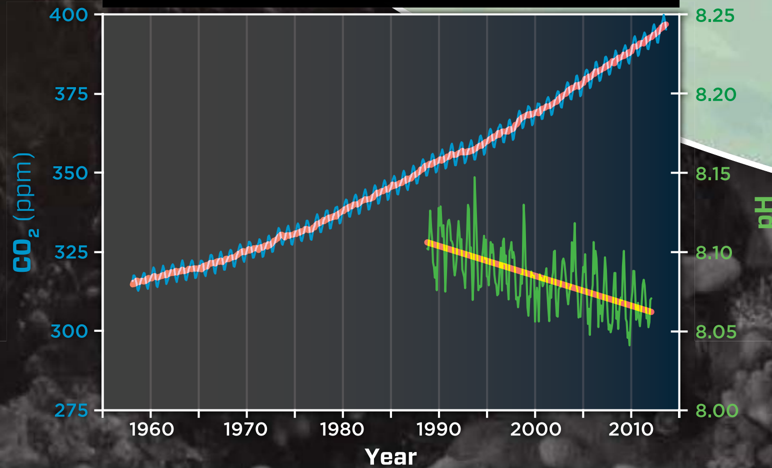
The pH scale measures the acidity of water-based solutions. A pH value below 7 indicates an acid; above 7 indicates an alkali. A pH decrease of one unit translates to a 10-fold increase in acidity. The average pH of ocean surface waters has fallen by about 0.1 units, from 8.2 to 8.1, since the beginning of the industrial revolution[1]. This corresponds to a 26% increase in acidity.

ARCTIC
Arctic waters are acidifying faster than the global average because cold water is richer in CO_2 and melting sea ice worsens the problem.



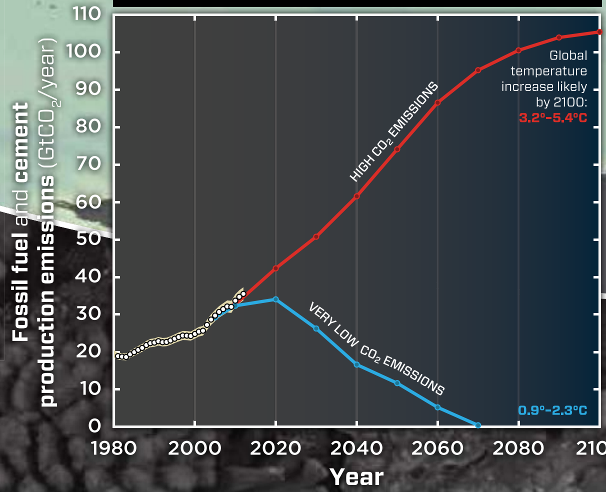
SPECIES SHIFTS
Some species, like seagrasses, may thrive in more acidified waters. Others may struggle to adapt. Any resulting losses of species could lead to lower biodiversity, a mark of ecosystem health.

Atmospheric CO_2 and ocean pH



Observations of CO_2 (parts per million) in the atmosphere and pH of surface seawater from Mauna Loa and Hawaii Ocean Time-series (HOT) Station Aloha, Hawaii, North Pacific.
Credit: Adapted from Richard Feely (NOAA), Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends) and Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu)

Observed CO_2 emissions and emissions scenarios to 2100



Global CO_2 emissions (white dots, uncertainty in grey) from fossil fuel use is following the high emissions trajectory (red line, RCP* 8.5) predicted to lead to a significantly warmer world. Large and sustained emissions reductions (blue line, RCP* 2.6) are required to increase the likelihood of remaining within the internationally agreed policy target of 2°C.
Credit: Glen Peters and Robbie Andrew (CICERO) and the Global Carbon Project, adapted from Peters *et al.*, 2013 (reference 8). Historic data from Carbon Dioxide Information Analysis Center.

* Intergovernmental Panel on Climate Change emissions scenarios — Representative Concentration Pathways (reference 1).

OCEAN ACIDIFICATION IN NUMBERS

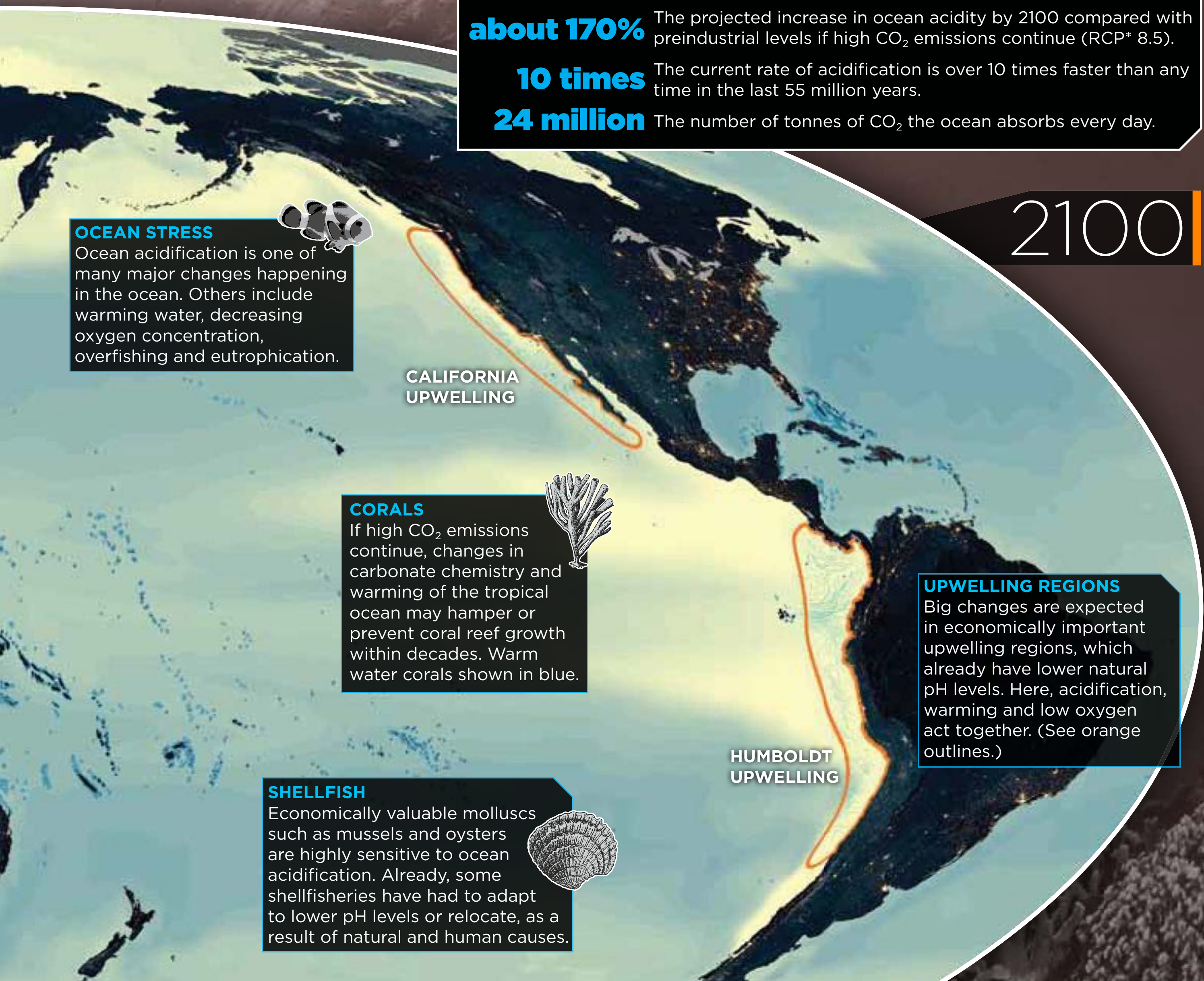
40% The increase in atmospheric carbon dioxide (CO_2) levels since the start of the industrial revolution.

26% The increase in ocean acidity from preindustrial levels to today.

about 170% The projected increase in ocean acidity by 2100 compared with preindustrial levels if high CO_2 emissions continue (RCP* 8.5).

10 times The current rate of acidification is over 10 times faster than any time in the last 55 million years.

24 million The number of tonnes of CO_2 the ocean absorbs every day.



OCEAN STRESS

Ocean acidification is one of many major changes happening in the ocean. Others include warming water, decreasing oxygen concentration, overfishing and eutrophication.

CORALS

If high CO_2 emissions continue, changes in carbonate chemistry and warming of the tropical ocean may hamper or prevent coral reef growth within decades. Warm water corals shown in blue.

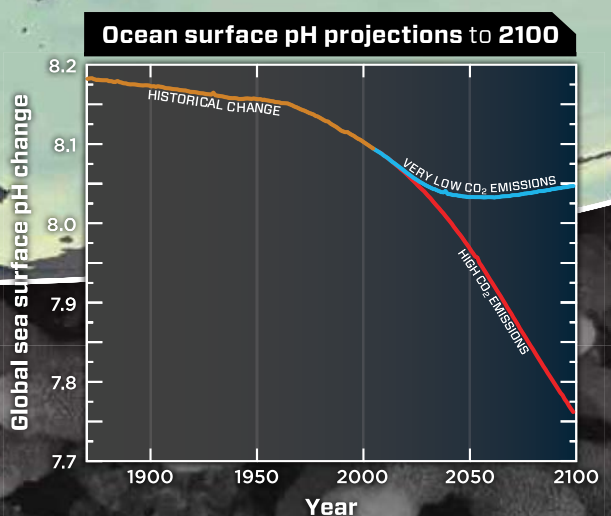
UPWELLING REGIONS

Big changes are expected in economically important upwelling regions, which already have lower natural pH levels. Here, acidification, warming and low oxygen act together. (See orange outlines.)

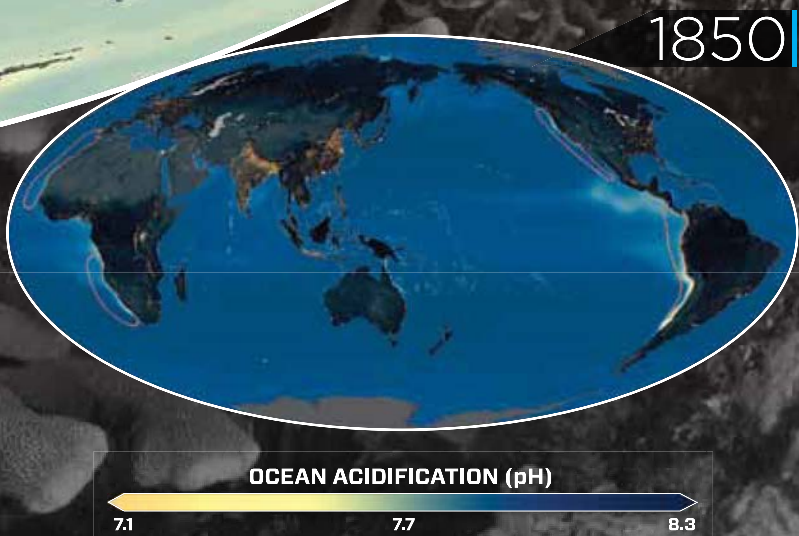
SHELLFISH

Economically valuable molluscs such as mussels and oysters are highly sensitive to ocean acidification. Already, some shellfisheries have had to adapt to lower pH levels or relocate, as a result of natural and human causes.

Ocean surface pH projections to 2100



Modelled global sea-surface pH from 1870 to 2100. The blue line reflects estimated pH change resulting from very low CO_2 emissions to the atmosphere (IPCC Representative Concentration Pathway, RCP* 2.6). The red line reflects pH from high CO_2 emissions (the current emissions trajectory, RCP* 8.5).
Credit: Adapted from Bopp *et al.*, 2013 (reference 9).



Ocean acidification maps: model projections are calculated by MPI-ESM-LR; data provided by Tatiana Ilyina from Ocean Biogeochemistry Group, Max Planck Institute for Meteorology.
Design: Félix Pharand-Deschênes, Globaïa.

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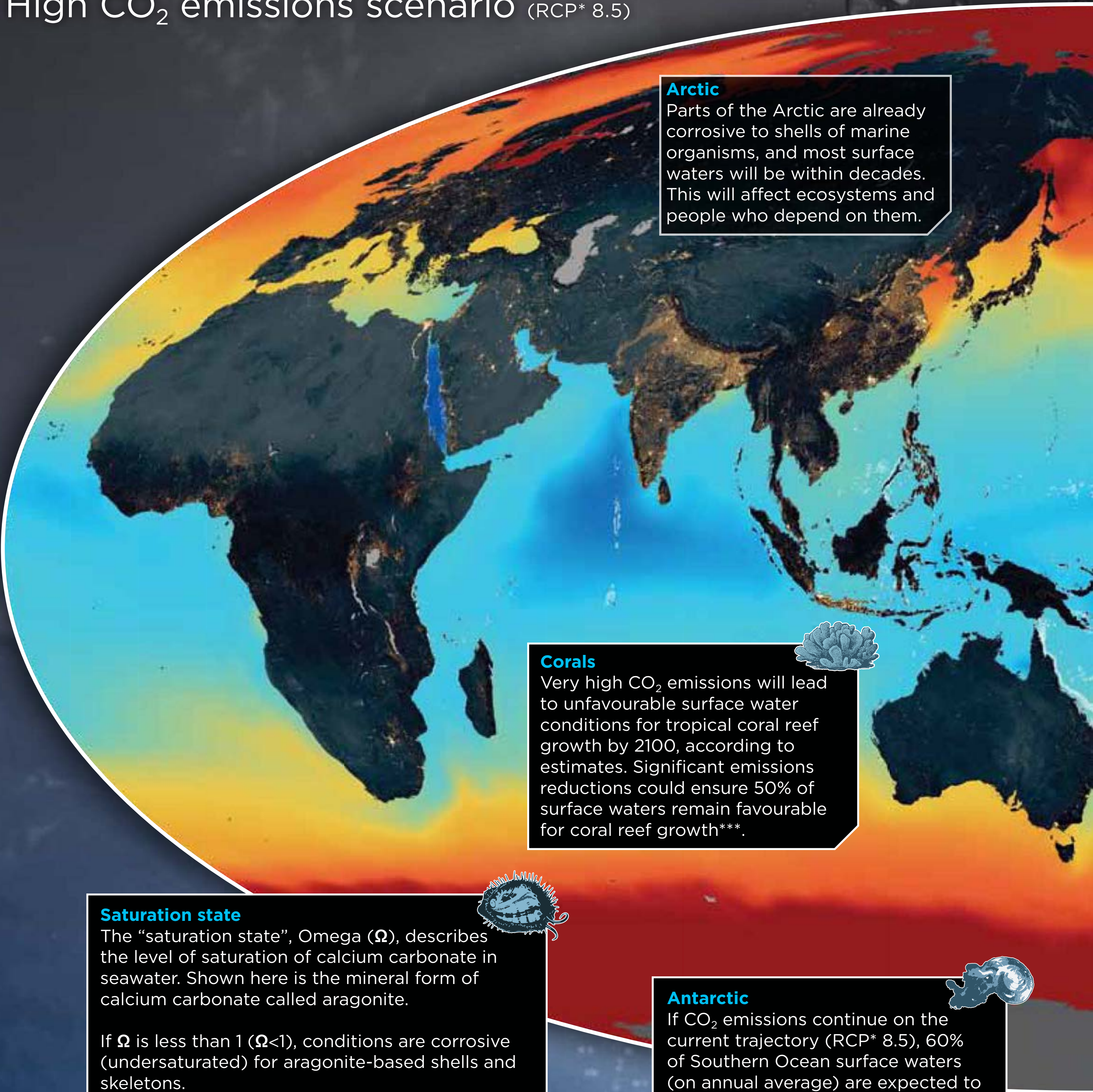
Aragonite saturation in 2100

High CO_2 emissions scenario (RCP* 8.5)



Arctic
Parts of the Arctic are already corrosive to shells of marine organisms, and most surface waters will be within decades. This will affect ecosystems and people who depend on them.

Corals
Very high CO_2 emissions will lead to unfavourable surface water conditions for tropical coral reef growth by 2100, according to estimates. Significant emissions reductions could ensure 50% of surface waters remain favourable for coral reef growth***.

Saturation state
The "saturation state", Omega (**Ω**), describes the level of saturation of calcium carbonate in seawater. Shown here is the mineral form of calcium carbonate called aragonite.

If **Ω** is less than 1 (**Ω**<1), conditions are corrosive (undersaturated) for aragonite-based shells and skeletons.

When **Ω**>1, waters are supersaturated with respect to calcium carbonate and conditions are favourable for shell formation. Coral growth benefits from **Ω**≥3.

By 2100, computer model projections show that **Ω** will be less than 3 in surface waters around tropical reefs if CO_2 emissions continue on the current trajectory***.

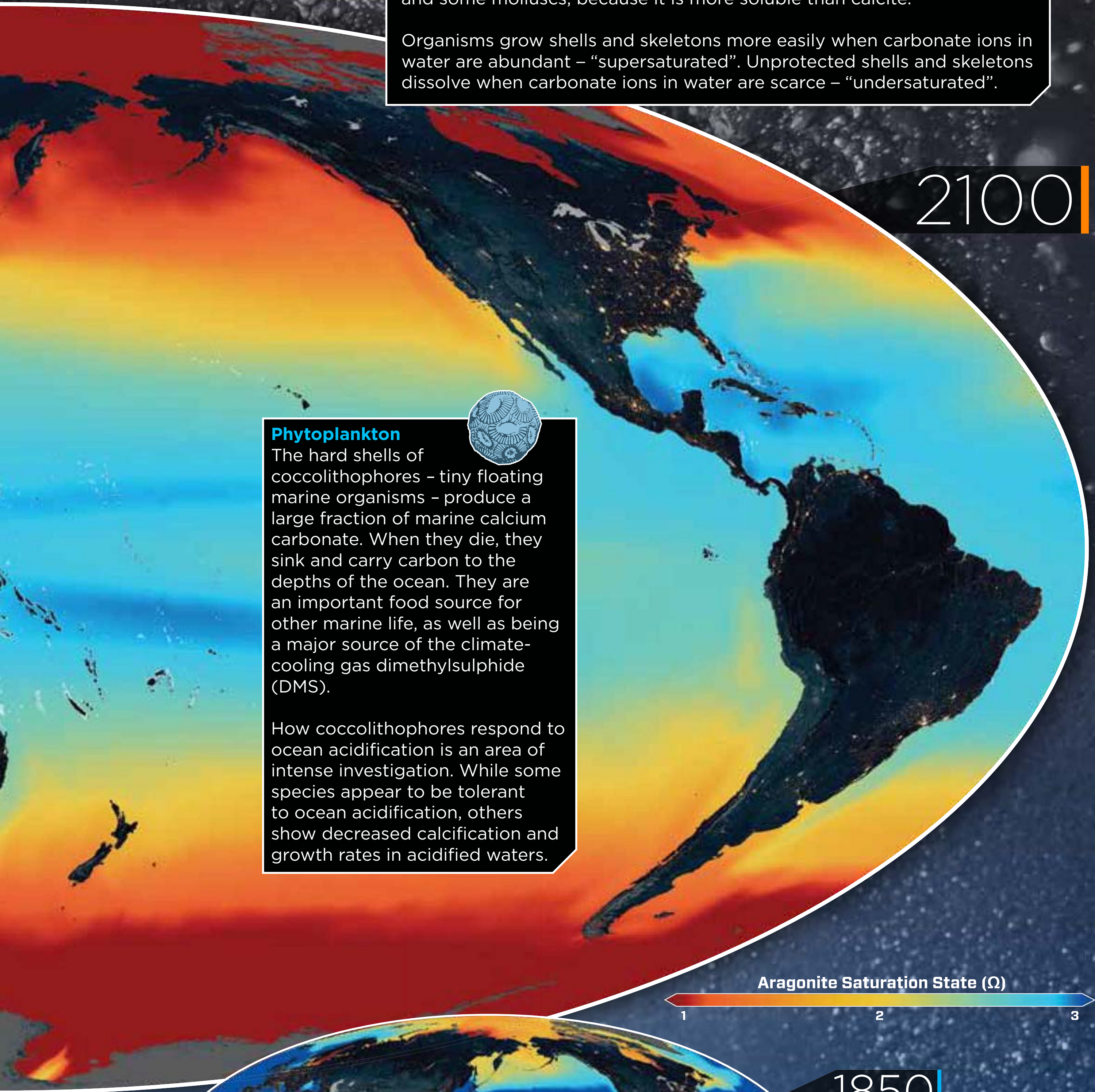
Antarctic
If CO_2 emissions continue on the current trajectory (RCP* 8.5), 60% of Southern Ocean surface waters (on annual average) are expected to become corrosive to the aragonite-shelled organisms, for example pteropods, which are part of the marine food web. Substantial emissions reductions (RCP* 2.6) could prevent most of the Southern Ocean surface waters from becoming corrosive to the shells of aragonitic organisms**.

* Intergovernmental Panel on Climate Change emissions scenarios — Representative Concentration Pathways (reference 1).
** Personal communication: Joos & Steinacher, after Steinacher *et al.*, 2013 (reference 10).
*** Ricke *et al.*, 2013 (reference 11).

Shells and skeletons

The shells and skeletons of many marine organisms are made from either calcite or aragonite; both are forms of calcium carbonate. Scientists are particularly interested in aragonite, which is produced by many corals and some molluscs, because it is more soluble than calcite.

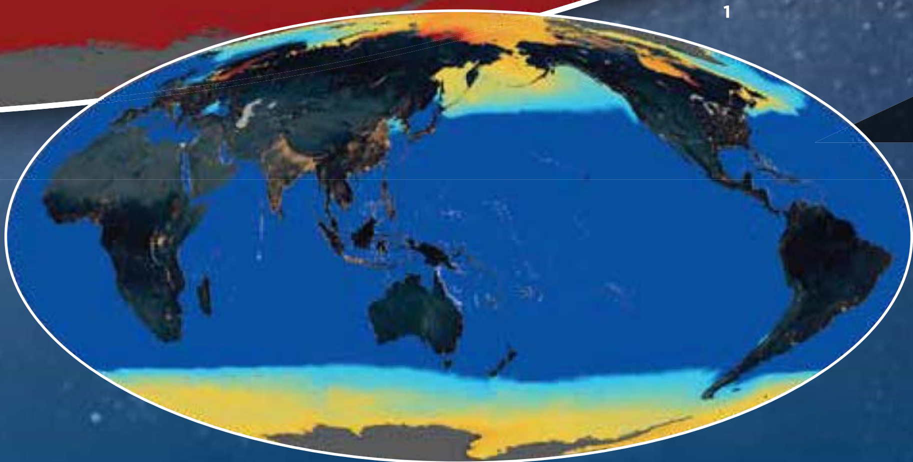
Organisms grow shells and skeletons more easily when carbonate ions in water are abundant – "supersaturated". Unprotected shells and skeletons dissolve when carbonate ions in water are scarce – "undersaturated".



Phytoplankton

The hard shells of coccolithophores – tiny floating marine organisms – produce a large fraction of marine calcium carbonate. When they die, they sink and carry carbon to the depths of the ocean. They are an important food source for other marine life, as well as being a major source of the climate-cooling gas dimethylsulphide (DMS).

How coccolithophores respond to ocean acidification is an area of intense investigation. While some species appear to be tolerant to ocean acidification, others show decreased calcification and growth rates in acidified waters.



Ocean acidification maps: model data provided by Tatiana Ilyina from Ocean Biogeochemistry Group, Max Planck Institute for Meteorology.
Design: Félix Pharand-Deschênes, Globaïa.

International research coordination


Ulf Riebesell; GEOMAR

- Research to decrease uncertainties is urgently needed. A coordinated **global network of marine experimental, observation and modelling research** is critical. Priority areas of research are responses of key species and entire ecosystems, particularly over longer time periods; the potential for organisms to adapt; socio-economic impacts; and the biogeochemical feedbacks on the climate system.
- In June 2012 at the UN's Rio+20 summit, the **Ocean Acidification International Coordination Centre** was announced. The centre, based at the International Atomic Energy Agency's Marine Environmental Laboratories in Monaco, will facilitate, communicate and promote international activities in ocean acidification research and observation and link science with policy.
- A **Global Ocean Acidification Observing Network**[12] was established in June 2012, working closely with the International Coordination Centre. Globally, relatively few sites have multi-decadal measurements and remote regions are poorly covered. The network will measure chemical and ecosystem variables needed to provide a baseline for the timely assessment of ocean acidification impacts. It will ensure data quality and comparability, and it will synthesise information for societal benefit.
- Significant investment to monitor ecosystem impacts will be a key aspect of future international research coordination activities.
- **Future Earth**, the International Council for Science's new 10-year international research initiative on global sustainability, will provide a mechanism for developing an internationally coordinated research agenda that will include issues like ocean acidification.

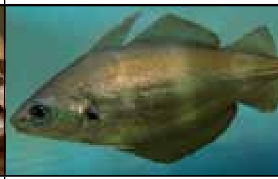
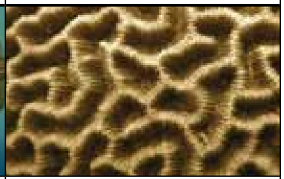
Stakeholder engagement

Effective knowledge exchange among science, policy and industry sectors is essential for effective adaptation and mitigation. A forum for dialogue between the research community and stakeholders – the **Ocean Acidification international Reference User Group** – has been established, building on a previous European initiative. It will draw together a wide range of end users and leading scientists to facilitate rapid transfer of knowledge.

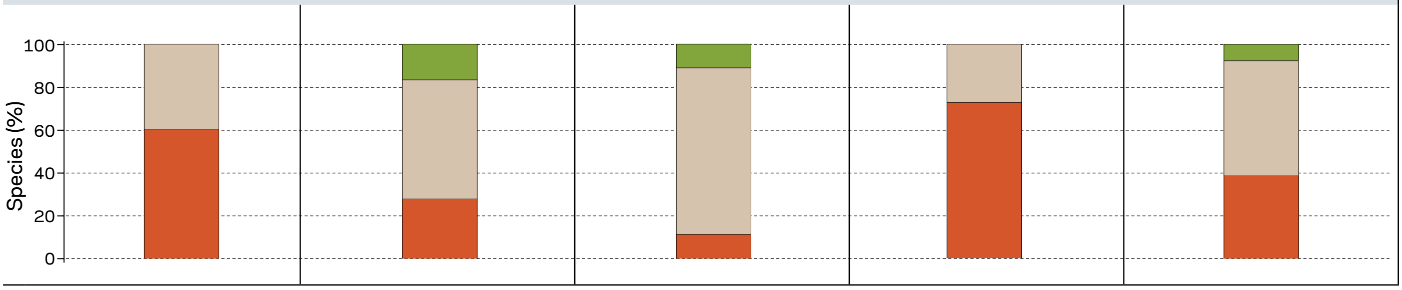
In addition, Future Earth (see above) aims to provide a platform for solutions-focused dialogue on global issues including ocean acidification.

Commercially and ecologically important organisms

Scientific research shows the vulnerability and sensitivity of commercially and ecologically important marine species to ocean acidification at elevated levels of CO_2 (adapted from Turley and Boot, 2011[13], and Wittmann and Pörtner, 2013[14]).

GROUPS					
	Molluscs	**Echinoderms**	**Crustaceans**	**Finfish**	**Corals**
					
	Clams, scallops, mussels, oysters, pteropods, abalone, conchs and cephalopods (squid, cuttlefish and octopuses)	Sea urchins, sea cucumbers, starfish	Shrimps, prawns, crabs, lobsters, copepods (zooplankton), etc.	Small (herrings, sardines, anchovies), large (tuna, bonitos, billfishes), demersal (flounders, halibut, cod, haddock), etc.	Warm and cold water coral
Ecosystem role	Mussels and pteropods are an important food source for fish, including salmon (pteropods). Mussels and oysters provide habitats for other organisms.	Keystone species and a food source for fish. Starfish are important predators.	Zooplankton such as copepods play a central role in food webs, connecting phytoplankton (which they eat) to predators (fish and mammals).	Major role in the balance of ecosystems as top predators or in connecting important trophic levels.	Important ecosystem engineers, providing habitat for a wide range of marine species, many of which are specialised to living in coral reefs.
Current estimated global commercial value◆	\$24 billion Locally important. Direct protein source in some island states.	\$0.7 billion Locally important. "Luxury" food item; sea cucumbers are used extensively in Chinese traditional medicine.	\$37 billion	\$65 billion Significant proportion of human food, fish-oil manufacture and fish meal. Locally important: dependence for food and income in some areas.	\$30–375 billion◇ These hotspots of marine biodiversity provide coastal protection, attract tourists and support fisheries.
Vulnerability	Adults and juveniles have shown reduced calcification, growth and survival rates. Some species may become locally extinct.	Few species studied. Vulnerability in early life stages. Some species may become locally extinct.	Less affected than other groups. Thermal tolerance of some crabs is reduced with acidification.	Indirect effects due to changes in prey and loss of habitats such as corals likely. Possibly some direct effects on behaviour, fitness and larval survival.	Reduced calcification, increased bio-erosion, synergistic effects of warming and acidification.

Sensitivity (percent of species affected)△



Effects
- Positive
- None
- Negative

◆ Commercial value for fisheries represents the sum of capture fisheries and aquaculture in 2010 in US dollars[15].

◇ Today's estimated value of global goods and services provided by coral reefs, such as coastline protection, tourism, biodiversity and food[16,17].

△ Adapted from Wittmann and Pörtner, 2013[14]. These data are for business-as-usual trajectories of CO_2 levels.

Societies and economies

Societies depend on the ocean for various ecosystem services:

- provisioning services, such as food;
- regulating services, such as carbon absorption from the atmosphere;
- cultural services, such as recreation; and
- supporting services, such as nutrient cycling.

While much is known about the effects of ocean acidification on individual organisms, the potential responses of whole ecosystems are largely unknown. Thus, although deleterious consequences are expected for shellfish and warm water corals (high confidence) and fisheries (low confidence), it is difficult to quantify how the ecosystems and fisheries will change and how societies will adapt to and manage the changes.

Confidence levels

In this document, we use these confidence levels (right). For further information on how these levels are determined, see the scientific background.

- V — Very High Confidence
- H — High Confidence
- M — Medium Confidence
- L — Low Confidence

V The capacity of the ocean to act as a carbon sink decreases as it acidifies [Very High Confidence]

The ocean provides a vast sink for anthropogenic CO_2 emissions. Around one quarter of annual CO_2 emissions from human activities currently end up in the ocean[18]. This service cannot be relied on in the future. Atmospheric CO_2 is rising faster than the ocean can respond. The capacity of the ocean to absorb CO_2 decreases as ocean pH decreases; that is, the buffering capacity of seawater decreases[19]. This reduced capacity is a concern for stabilising CO_2 emissions and implies that larger emissions cuts will be needed to meet targets to mitigate climate change.

M Declines in shellfisheries will lead to economic losses [Medium Confidence], but the extent of the losses is uncertain

By 2100, estimated global annual economic losses due to declines in mollusc production from ocean acidification could be more than $130 billion (US dollars, at 2010 price levels) for a business-as-usual CO_2 emissions trend, according to one estimate[20] [low confidence]. For the United States, a 13% reduction in revenue is estimated by 2060 from declines in mollusc harvests due to acidification[21] [low confidence]. Economically important shellfish species may respond in different ways to ocean acidification (see table on p. 9), but we do not know enough to make quantitative economic predictions for all fisheries yet.

Molluscs appear to be one of the most sensitive groups of organisms studied under ocean acidification regimes. Indeed, oyster larvae in hatcheries in the northeast Pacific Ocean region are very sensitive to ocean acidification and are already affected by low pH waters[22,23].

Social consequences

The examples illustrated here highlight the potential for substantial revenue declines, loss of employment and livelihoods, and indirect economic costs that may occur if ocean acidification damages marine habitats, alters marine resource availability, and disrupts other ecosystem services.

The current estimates of economic impacts are largely restricted to commercially marketed ecosystem services such as fisheries and tourism. A full assessment must take into account ecosystem services beyond those that are directly market-based, such as cultural services, regulating services (such

M Negative socio-economic impacts of coral reef degradation are expected [MEDIUM CONFIDENCE], but the size of the costs is uncertain

Substantial economic losses are likely to occur due to the loss of tropical coral reef extent from ocean acidification (by 2100, the scarcity of corals will push the value of their losses over $1 trillion per year, in US dollars at 2010 price levels, according to one estimate[24]) [LOW CONFIDENCE]. A large proportion of these losses will occur in vulnerable societies and small island states that economically rely on coral reefs. Coral reef losses will negatively affect tourism, food security, shoreline protection and biodiversity. But ocean acidification is not the only stressor. Reefs are already under pressure from warmer temperatures (which cause coral bleaching), habitat destruction, overfishing, sedimentation and pollution.

Actions that slow the rate of ocean acidification will reduce impacts and maximise the potential for coral reefs to recover, and even adapt, to other stressors. Thus, additional human stressors, such as destructive fishing practices, pollution and sedimentation, will not only have immediate ecological effects, they will also reduce the potential of coral reefs to adapt to warmer, more acidified conditions.

In addition to global climate policy, local reef management strategies – implemented using tools such as Marine Protected Areas, fisheries management, and marine spatial planning – also increase the potential of coral reefs to cope with ocean acidification[4,25].

L Impacts of ocean acidification on ecosystems may affect top predators and fisheries [LOW CONFIDENCE]

It is uncertain how changes in phytoplankton and zooplankton abundance and distribution will propagate through marine ecosystems to affect fish and fisheries, on which many societies depend. Also, very little is known about the direct effects of ocean acidification on fish that are the target of commercial and subsistence fishing, which results in high uncertainties in predicting changes in fisheries in the future. However, this area is key for research, as fisheries support the livelihoods of about 540 million people, or 8% of the world's population[26].

as coastal protection) and a broader set of provisioning services (such as marine-derived pharmaceuticals).

To a large extent, societies that are highly vulnerable to ocean acidification are located in developing countries or small island states[27]. Their inhabitants rely on fish and other marine resources as their primary source of protein. In addition, indigenous peoples and cultures in the Arctic – where the ocean is acidifying more rapidly than in other locations – are also dependent on natural resources, and therefore these societies are potentially vulnerable.

Thresholds

Can scientists define a "safe" or "tolerable" level of ocean acidification that must not be exceeded?

Some decision makers are asking scientists if it is possible to begin defining thresholds beyond which ecosystems will not recover. This is a complex challenge. The combined effects of changing ocean physics, chemistry and biology vary from ecosystem to ecosystem. Impacts are also dependent on geographic location and variable local characteristics.

Ecosystem impacts depend on policy decisions made now in relation to future carbon dioxide emissions and policies relating to other marine issues. Moreover, there are complex ethical and economic considerations on issues relating to "safe" or "tolerable" levels of ocean acidification.

Science cannot answer these questions but can provide some information on possible consequences of policy options. A dialogue between scientists, policymakers and stakeholders is necessary to explore what questions require answers and what options are available.

A first step towards identifying thresholds and indicators will be a concerted global research effort. This should combine experiments, models and observations to attempt to untangle the complexity of the response of marine ecosystems to ocean acidification and other stressors and will be led by the newly established International Coordination Centre.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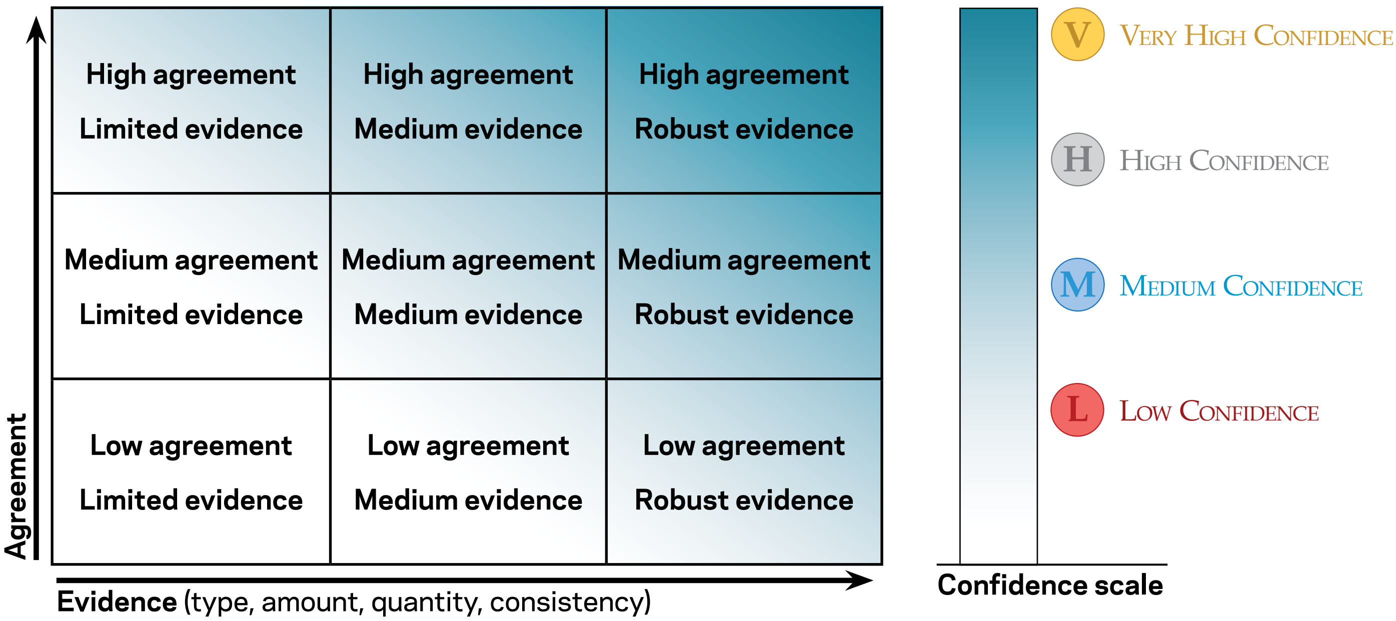
Scientific background

Ocean acidification research is relatively new. The numbers of scientists involved and research papers published are increasing rapidly. New discoveries are frequent and our understanding is being continually refined.

Defining confidence levels

Confidence levels are expressed in this document with the qualifiers "low", "medium", "high" and "very high". These qualifiers synthesise the authors' judgments about the validity of findings as determined through evaluation of evidence and agreement. The analysis builds on statements of confidence derived from peer-reviewed synthesis such as the European Project on Ocean Acidification synthesis book[28] and the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. The most recent meta-analyses, of 228 ocean acidification studies on marine organisms[29] and 167 studies on marine animals[14], provided further evidence to aid the authors in analysing and summarising the outcomes of the experimental evidence. Increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see figure), as outlined in the IPCC's guidance note on the treatment of uncertainties[30] in the Fifth Assessment Report.



The ocean is acidifying rapidly and at an unprecedented rate in Earth's history

The chemistry of ocean acidification is well understood, and scientists have well-constrained models that can predict changes in the surface ocean chemistry as CO_2 increases in the atmosphere. When CO_2 gas dissolves in seawater, carbonic acid is formed, changing the chemical composition of the ocean: ocean acidification.

V Ocean acidification is caused by CO_2 emissions from human activity to the atmosphere that end up in the ocean [Very High Confidence]

The ocean currently absorbs approximately a quarter of the CO_2 added to the atmosphere from human activities each year[18], greatly reducing the impact of this greenhouse gas on climate.

V Anthropogenic ocean acidification is currently in progress and is measurable [Very High Confidence]

Anthropogenic CO_2 emissions are causing chemical changes in the ocean that are observable now and are highly predictable at a global scale into the future.

The acidity of surface ocean waters has increased about 26% since the beginning of the industrial revolution[1]. With increasing dissolved CO_2, calcifying organisms will find it more difficult to build their shells.

H The ocean is acidifying more rapidly than it has in millions of years [High Confidence]

Today's human-induced acidification is a unique event in the geological history of our planet due to its rapid rate of change.

An analysis of ocean acidification over the last 300 million years highlights the unprecedented rate of change of the current acidification[31]. The most comparable event 55 million years ago was linked to mass extinctions of calcareous deep-sea organisms and significant changes to the surface ocean ecosystem[31]. At that time, though the rate of change of ocean pH was rapid, it may have been 10 times slower than current change[32].

V The legacy of historical fossil fuel emissions on ocean acidification will be felt for centuries [Very High Confidence]

The increase in atmospheric CO_2 is occurring too quickly to be stabilised by natural feedbacks such as the dissolution of deep-sea carbonates, which acts on time-scales of thousands of years, or the weathering of terrestrial carbonate and silicate rocks, which operates on time-scales of tens to hundreds of thousands of years.

Global-scale projections of the changing chemistry of seawater can be made with high accuracy from scenarios of atmospheric CO_2 levels. Even if anthropogenic CO_2 emissions stopped today, the ocean's pH would not recover to its preindustrial level for centuries[33].

V Reducing CO_2 emissions will slow the progress of ocean acidification [Very High Confidence]

The concentration of atmospheric CO_2 is approximately 395 parts per million (ppm; global average, as of 2013), which is more than 40% higher than the preindustrial level of 280 ppm. Half of this increase has occurred in the last 33 years[34]. If CO_2 emissions are reduced, less CO_2 will enter the ocean, limiting the extent of ocean acidification impacts[33].

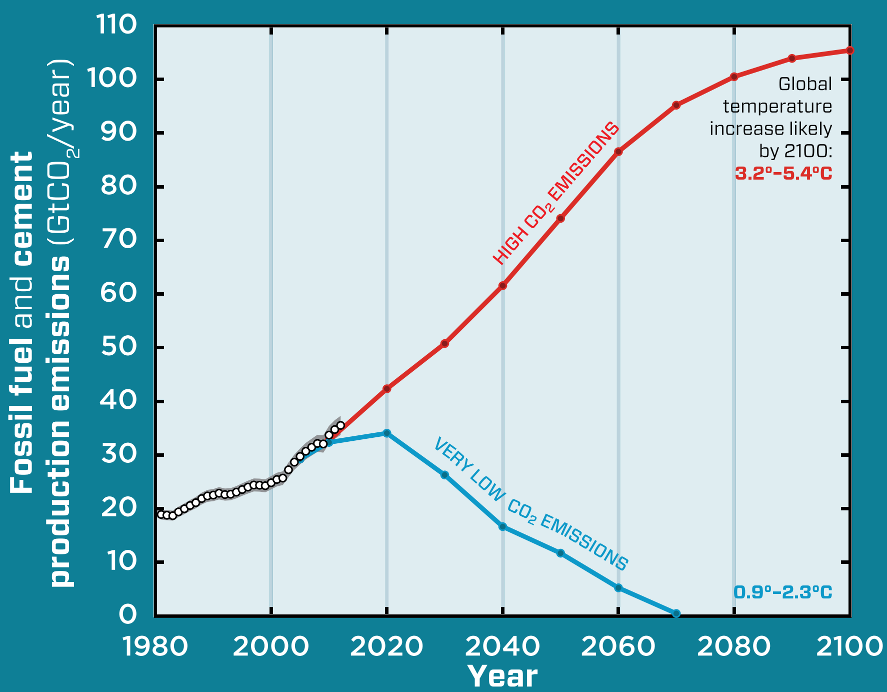
Reducing CO_2 emissions is possible with existing or developing technology. Currently, there are agreements to stabilise CO_2 emissions to limit the global mean temperature increase to 2°C above preindustrial levels. These levels may still jeopardise the stability of some marine ecosystems. Current emissions are tracking a much higher global temperature increase (see box).

Future CO_2 emissions: Representative Concentration Pathways

Representative Concentration Pathways (RCPs) are future emissions pathways used in the Intergovernmental Panel on Climate Change's Fifth Assessment Report[1]. Many scenarios could lead to a particular pathway. The highest RCP (8.5 Wm^{-2} radiative forcing) represents high (business as usual) emissions. It results in mean global warming by 2100 of about 4.3°C (likely range, 3.2°–5.4°C) above preindustrial temperatures. The lowest RCP (2.6 Wm^{-2} radiative forcing) requires significant mitigation and emissions reductions resulting in a global average temperature rise of about 1.6°C (likely range, 0.9°–2.3°C) above preindustrial levels.

Global marine consequences

By 2100, business-as-usual emissions (RCP 8.5) would result in ocean acidification leading to the loss of 100% of tropical surface waters with conditions favourable for coral reef growth. Significant reductions (RCP 2.6) would result in less than half of this loss (personal communication, Joos and Steinacher[10,11]).



By 2100, 60% of the Southern Ocean surface waters (on average) could become corrosive to the shells of aragonitic organisms, a part of the marine food chain, if emissions continue along a business-as-usual trajectory (RCP 8.5). With strong mitigation (RCP 2.6), corrosive conditions in most of the Southern Ocean can be avoided (personal communication, Joos and Steinacher[10]).

Global CO_2 emissions (white dots, uncertainty in grey) from fossil fuel use are following the high emissions trajectory (red line, RCP 8.5) predicted to lead to a significantly warmer world. Large and sustained emissions reductions (blue line, RCP 2.6) are required to increase the likelihood of remaining within the internationally agreed policy target of 2°C.

Source: Glen Peters and Robbie Andrew (CICERO) and the Global Carbon Project, adapted from Peters *et al.*, 2013[8]. Historic data from Carbon Dioxide Information Analysis Center.

How will marine organisms respond?

Most of what is known about organismal responses to ocean acidification has been obtained from relatively short-term laboratory experiments on single species. Such experiments use simplified versions of the natural environment, but give an indication of potential responses in the ocean[28].

In a growing number of laboratory and field experiments multiple organisms are studied together, for example, in gradients of pH in naturally acidified ecosystems and in mesocosms with natural communities including numerous species.

Results from a broad range of marine organisms show various responses, including decreased survival, calcification, growth, development and abundance. There is considerable variation in the sensitivity and tolerance of marine organisms to ocean acidification, sometimes even within a single species. Other organisms show a positive response to the increased availability of CO_2. More active organisms, such as mobile crustaceans and fish, seem to be less sensitive to ocean acidification. Fleshy algae, some phytoplankton and some seagrasses may benefit from an increase in carbon availability. The impacts on individual species – whether they decline or benefit from ocean acidification – may cause cascading disturbances in other parts of the food web.

M Anthropogenic ocean acidification will adversely affect many calcifying organisms [MEDIUM CONFIDENCE]

Most studies demonstrate that calcification – the ability for some organisms to produce shells or skeletons – decreases with ocean acidification[29]. These include planktonic calcifiers (such as foraminifera, coccolithophorids and pteropods), corals and molluscs, as well as echinoderms (e.g., urchins) and less so crustaceans (e.g., crabs).

An analysis of ocean acidification studies shows that many calcifying organisms also show a decrease in survival, growth, development and abundance[29]. In many calcifying groups, early life stages are most sensitive to CO_2-induced changes in seawater chemistry. Crustaceans are less affected than corals, molluscs or echinoderms[14].

H Molluscs (such as mussels, oysters and pteropods) are one of the groups most sensitive to ocean acidification [HIGH CONFIDENCE]

Early life stages of many molluscs (larvae and juveniles) as well as adults have shown reduced calcification, growth and survival. This makes molluscs one of the groups most sensitive to ocean acidification[14].

M Pteropod (marine snail) shells are already dissolving [MEDIUM CONFIDENCE]

The high-latitude oceans are already becoming corrosive to some species. The shells of pteropods, small marine snails that are key species in the food web, are already dissolving in parts of the Southern Ocean, which surrounds Antarctica[35]. They have special importance in the food web in polar regions, for example forming a key food source for pink salmon[36].

H If CO_2 emissions continue on the current trajectory, coral reef erosion is likely to outpace reef building sometime this century [HIGH CONFIDENCE]

Ocean acidification alone is likely to cause reef building to cease by the end of the 21st century on the current CO_2 emissions trajectory[37]. If coral bleaching due to ocean warming is also taken into account, then the rates of erosion on most reefs could outpace the overall reef building by corals and other organisms once CO_2 levels reach 560 ppm (by mid-century under the current emissions trajectory)[38]. If this happens, the degradation and loss of coral reefs will affect whole ecosystems dependent on reefs as habitat, with consequences for biodiversity, fisheries and coastal protection. Very aggressive reductions in CO_2 emissions are required to maintain a majority of tropical coral reefs in waters favourable for growth[11].

Cold-water coral communities are at risk [High Confidence], and may become unsustainable

By 2100, it is estimated that 70% of cold-water corals will be exposed to corrosive waters, although some will experience undersaturated waters as early as 2020[39]. Undersaturated conditions will increase the dissolution rate of the dead skeletons (the base of these deep-water coral communities), which will lead to a disintegration of the cold-water coral ecosystems[40,41]. Their loss would have consequences for food webs[42], as they provide habitat, feeding grounds and nursery areas for many deep-water organisms.

Ocean chemistry for shell and skeleton formation

In the ocean, CO_2 reacts with water and carbonate ions to create carbonic acid. Elevated CO_2 levels reduce the concentration of carbonate ions. Shells of many marine organisms are made of calcium carbonate, which has two main forms: calcite and aragonite. Both minerals dissolve at low carbonate ion concentrations – known as "undersaturated conditions" – unless the calcifying organisms have evolved mechanisms to prevent dissolution, such as protective layers or other means to isolate their carbonate structures from exposure to corrosive water[43]. Aragonite, which is formed by corals, by the first larval stages of many molluscs, and by some adult molluscs (including pteropods), is more soluble than calcite, which is produced by coccolithophores, foraminifera, echinoderms and crustaceans.

The scale for describing the level of saturation of calcium carbonate in seawater is the "saturation state", Omega (Ω), where $\Omega < 1$ indicates undersaturated (corrosive) and $\Omega > 1$, supersaturated waters.

In an acidifying ocean, skeletal and shell growth generally slows down significantly as the saturation state decreases. For example, coral growth benefits from high aragonite saturation states, larger than 3 ($\Omega \geq 3$)[44].

Conditions in the deep

Deep waters naturally contain more CO_2 and have a lower pH compared with the surface ocean. Furthermore, calcite and aragonite saturation decreases with increasing pressure. The boundary between these deeper undersaturated waters and the shallower saturated waters is known as the "saturation horizon".

Increasingly, the aragonite saturation horizon is becoming shallower and thus corrosive conditions for shell-forming organisms are moving closer to the surface.

This process is well understood and well documented at a global scale. The saturation horizon will reach the ocean surface by the end of this century in the North Pacific, the Arctic seas and Southern Ocean, under RCP 8.5 (see p. 15).

In upwelling areas such as in the northeast Pacific Ocean and along the western coasts of South America and Africa, naturally more acidic deep waters upwell onto continental shelves. The ocean uptake of anthropogenic CO_2 has increased the extent of the areas affected by more acidic waters[45], which include important fisheries grounds.

Christina Kellogg; USGS

M Ocean acidification may have some direct effects on fish physiology, behaviour and fitness [Medium Confidence]

Accumulation of CO_2 in animal bodies may disturb life processes, leading to overall changes in their fitness and physiology[46,47]. In general, fish appear to be less sensitive to ocean acidification than less mobile organisms. Ocean acidification has led to a decrease in growth rates of fish larvae[48].

There is some evidence that clown fish (which live in coral reefs) are altering their behaviour (smell, hearing, visual risk, etc.), decreasing their ability to detect predators and prey[49]. The long-term impacts are unclear, as the geological record does not indicate fish are sensitive to ocean acidification, as it does for some other organisms.

Overall, the changes in the food supply of fish are likely to have more significant effects on their abundance than the direct physiological effects.

H Some seagrass and phytoplankton species may benefit from ocean acidification [High Confidence]

Elevated levels of CO_2 appear to stimulate photosynthesis and growth in some groups of organisms. These include some seagrasses, fleshy algae and some phytoplankton groups (e.g., cyanobacteria and picoeukaryotes)[50]. Observations in ocean areas with naturally high CO_2 venting (e.g., the island of Ischia, Italy) show that marine plants prosper in the acidified waters[51].

H The combination of ocean acidification and increased temperatures negatively affects many organisms [High Confidence]

Ocean acidification appears to narrow the thermal tolerance of some organisms[56], and others are more vulnerable to ocean acidification in warmer waters. The response to both changes together is often larger than the response to those changes taken separately[52]. Studies show a trend towards lower survival, growth and development when elevated temperatures and ocean acidification occur together. The combination of ocean acidification and warming may result in shifts in species diversity and ecosystem composition by the reduction of habitat range.

Warm-water corals are also susceptible to bleaching during periods of unusual warmth. Several mass coral bleaching events have occurred since 1979, resulting in warm-water coral mortality worldwide[53]. Tropical coral reefs are particularly at threat from the combined effects of warming and ocean acidification.

How will marine ecosystems respond?

The varied responses of species to ocean acidification and other stressors are likely to lead to changes in marine ecosystems [HIGH CONFIDENCE], but the extent of the impact is difficult to predict

We know that some organisms, such as seagrasses and some phytoplankton, seem to thrive under acidified conditions, while others, such as corals and shellfish, are harmed. These sensitivities – combined with other related stressors such as global warming – are likely to lead to changes in species composition, thus changing food sources for predators. There are many uncertainties in our ability to predict these changes and their consequences, but there is high agreement among scientists that changes are likely to be significant[54].

Knowledge gaps that have to be filled are as follows: What will replace species that disappear? Will the role in the ecosystem of the replacement species be the same? What will be the consequences for ecosystems? How will this affect the biogeochemical cycles on which life depends? Will some species be able to adapt in time? (See adaptation box.) Are there carry-over effects from generation to generation?

Despite rapid advances in ocean acidification research, we are still unable to make reliable projections of the impacts on marine ecosystems and fisheries. How whole ecosystems respond to ocean acidification is thus a priority area of research. Laboratory studies and single-organism studies cannot simply be extrapolated to the whole ecosystem. However, there is enough evidence to allow scientists to draw some preliminary conclusions with various levels of confidence.

Adaptation

Acclimation is the ability of an individual organism to adjust to environmental change. Acclimation can occur at various time-scales within the lifetime of the organism. The responses, which are generally reversible, allow the organism to perform across a range of environmental conditions.

Adaptation is the evolutionary response of a population – over multiple generations – to a modified environment. The potential for evolutionary adaptation is highest in species with short generation times and large population sizes.

There is experimental evidence for evolutionary adaptation to ocean acidification in some short-lived microorganisms, including calcareous microalgae (coccolithophores)[55]. Members of this group have a high genetic diversity, short generation times of a day or less, and huge population sizes of up to a million cells per litre of seawater. In contrast, organisms with longer generation times, such as corals, may struggle to adapt with the magnitude and rate of ocean acidification that will occur in this century.

Short-term experimental studies of a species' response to environmental change do not generally account for adaptive processes. The observed responses may therefore overestimate the long-term sensitivity of natural populations to environmental change. However, mass extinctions seen in the geological record, in time periods when the rate of ocean change was much slower than it is today, suggest that evolutionary rates of some species may not be fast enough for them to adapt to the multiple environmental changes projected for the future ocean [HIGH CONFIDENCE].

Photo by NEON ja; coloured by Richard Bartz

H Multiple stressors compound the effects of ocean acidification [High Confidence]

The problems organisms face with ocean acidification are often compounded by other stressors, such as rising temperature[56], loss of oxygen (deoxygenation), ocean stratification[9,57], overexploitation, pollution, extreme events, increasing UV-B irradiance (due to stratospheric ozone depletion)[58] and changes in salinity. Some of these stressors are also caused by excess CO_2 in the atmosphere.

At a global level, increased stratification causes decreased productivity at low latitudes – towards the equator – where nutrients are limited. Additionally, large parts of the low-latitude ocean are vulnerable to deoxygenation as temperatures rise. The combined impact of ocean acidification and deoxygenation could result in far-reaching consequences on ocean biogeochemistry, such as the creation of large "dead zones" and increased marine denitrification and anaerobic ammonium oxidation, affecting the marine nitrogen cycle[9,57]. Changes in the deep ocean as a result of ocean acidification are poorly studied.

L Ocean acidification will alter biogeochemical cycles at a global scale [Low Confidence]

Changing ecosystem composition and the oceans' carbonate chemistry affects biogeochemical cycles in complex ways. Some organisms will thrive under ocean acidification and others will struggle. The changes to phytoplankton and zooplankton will in turn affect predators that rely on these organisms for food. Ocean acidification may also affect production of nitrous oxide, a potent greenhouse gas, and DMS, a climate-cooling compound. We need to understand ecosystem responses to the effects of ocean acidification on the cycling of key nutrients, in order to improve how global models simulate and predict biogeochemical changes[59].

M Nitrogen fixation in some cyanobacteria may be stimulated by ocean acidification [Medium Confidence]

There is some evidence that nitrogen fixation in some cyanobacteria will be stimulated by ocean acidification[54]. This process converts nitrogen gas to a biologically available form, providing a major input of nutrients into the ocean. This could have consequences for the nitrogen cycle and the productivity of the oceans, as large parts of the ocean are nitrogen-limited.

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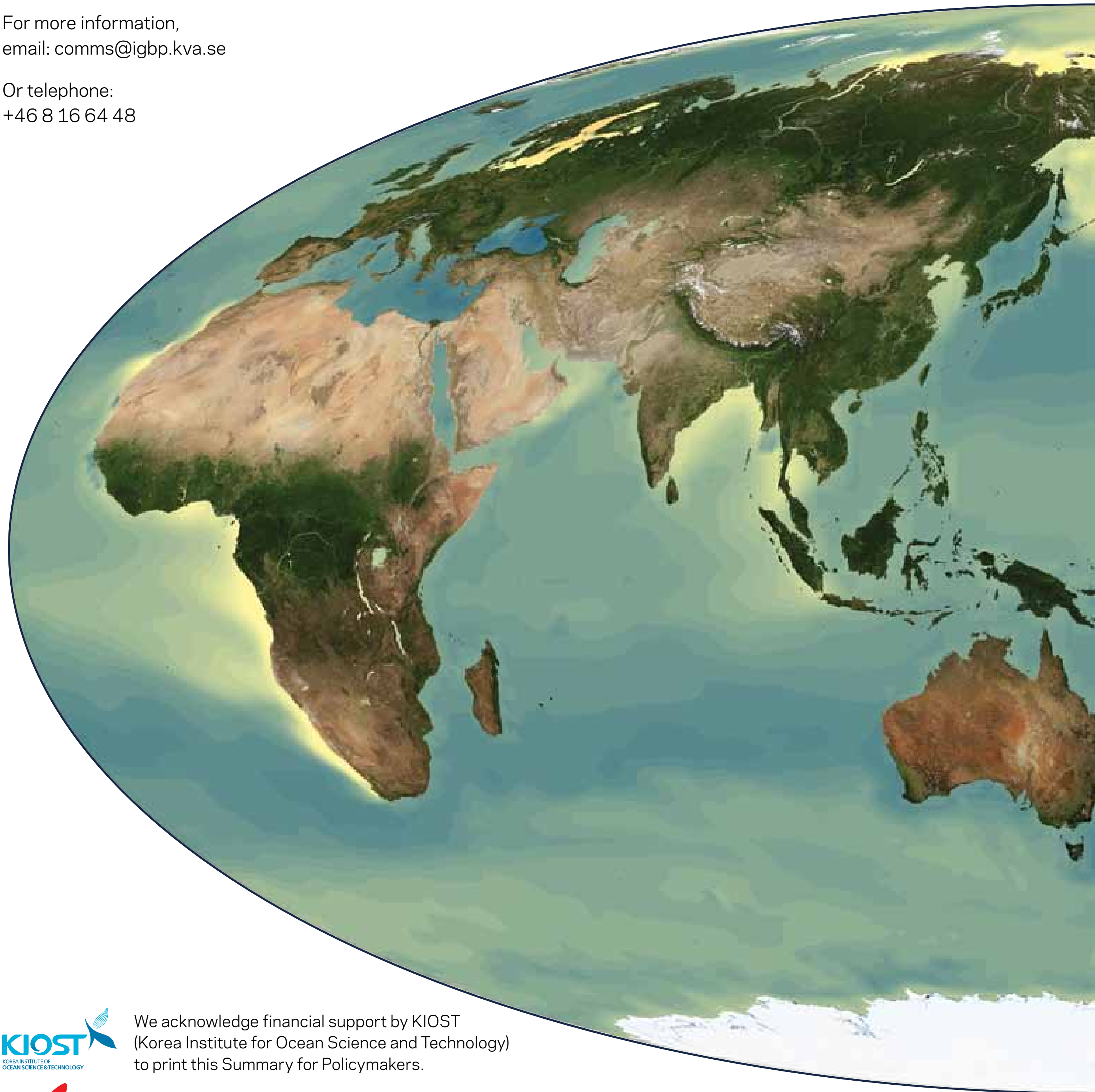

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