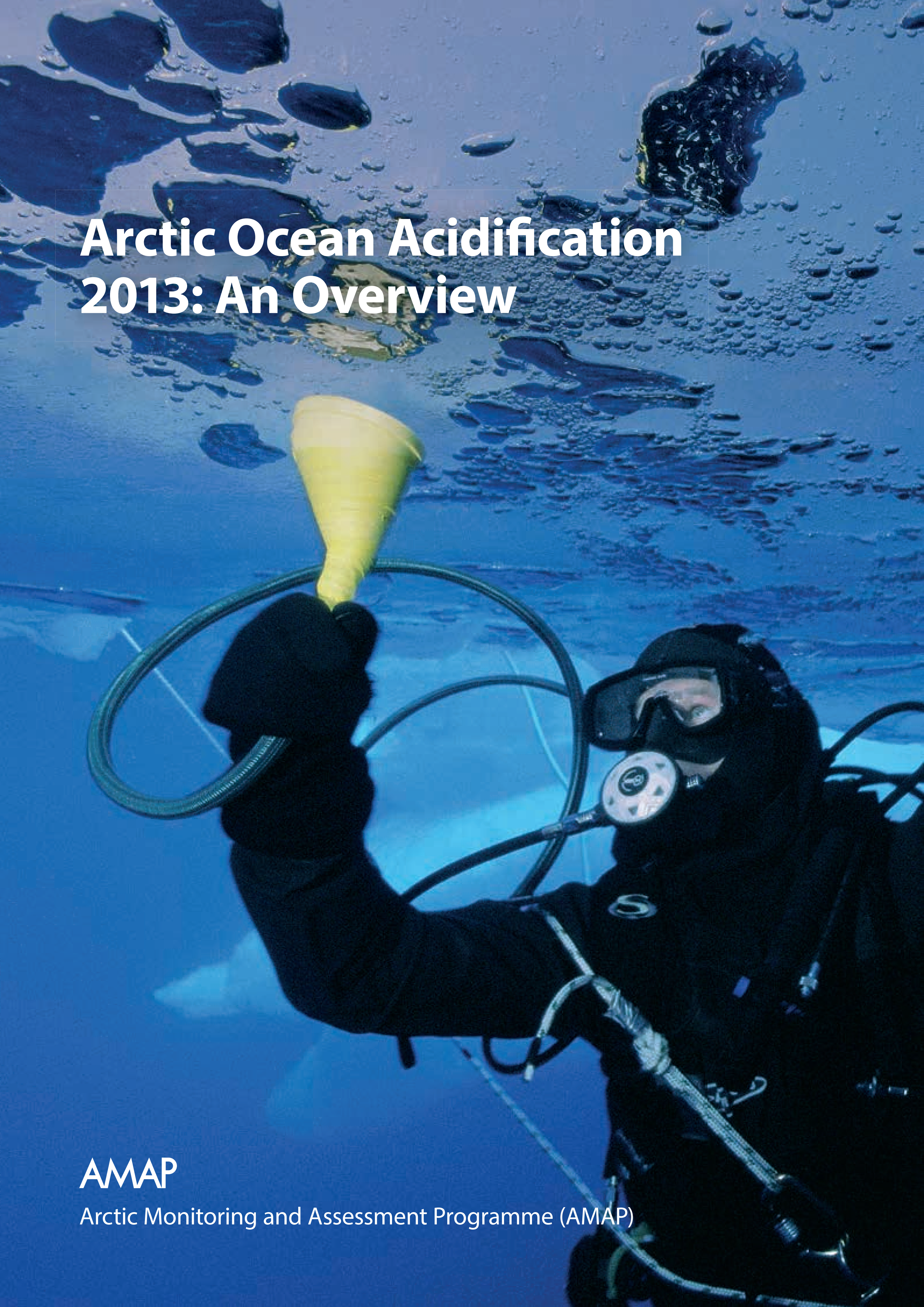
Arctic Ocean Acidification 2013: An Overview



AMAP

Arctic Monitoring and Assessment Programme (AMAP)

Arctic Ocean Acidification 2013: An Overview

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ARCTIC OCEAN ACIDIFICATION 2013: AN OVERVIEW

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PREFACE

This overview report presents a summary of the first comprehensive assessment of Arctic Ocean acidification (AOA) conducted by the Arctic Monitoring and Assessment Programme (AMAP).

More than 60 international experts collaborated to conduct the assessment, the scientific findings of which are documented in the ***AMAP Assessment 2013: Arctic Ocean Acidification*** report.[1] Additional experts provided independent review. In compiling this assessment, the AMAP team of experts identified significant gaps in critical data sets and current scientific understanding.

On the basis of the assessment, the AMAP Working Group developed the ***Arctic Ocean Acidification Assessment: Key Findings***[2] and ***Arctic Ocean Acidification Assessment: Summary for Policymakers***.[3] The Key Findings and associated recommendations, which were presented to the Arctic Council Ministers at their meeting in Kiruna, Sweden in May 2013, are reproduced in the executive summary that appears on pages ix-xi of this report. The response of the ministerial representatives of the Arctic Council is included in the box on page xi.

This overview report, ***Arctic Ocean Acidification 2013: An Overview,*** is also produced under the responsibility of the AMAP Working Group and is intended to provide a readable summary of the 2013 Arctic Ocean acidification assessment and its findings (summarised on page 26). It includes suggestions for advancing knowledge of Arctic Ocean acidification and its possible implications for the people of the Arctic (on page 25).

The fully referenced and peer-reviewed ***AMAP Assessment 2013: Arctic Ocean Acidification*** report constitutes the scientific basis for the majority of the information and graphics* presented in this overview report. The ocean-acidification assessment complements previous AMAP assessments of Arctic climate change, including the ***Arctic Climate Impact Assessment***[4] and the ***Snow, Water, Ice and Permafrost in the Arctic*** (SWIPA) assessment[5]. Where this overview report incorporates information from the SWIPA assessment, this is indicated by footnotes. Elements of this report that have been updated in light of new information in the Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[6] are also flagged using footnotes.

The AOA assessment was presented to the scientific community at the Arctic Ocean Acidification International Conference held in Bergen, Norway, in May 2013 (presentations are available at www.ustream.tv/channel/aoa-conference). Other AMAP AOA outreach products include films[7] produced to summarise the main findings of the AOA assessment for policymakers, educators and students. All AOA-related reports and films are available from the AMAP Secretariat and on the AMAP website (www.amap.no).

AMAP would like to express its appreciation to all those experts who contributed their time, effort and data to the AOA, especially the lead authors of the scientific assessment. Special thanks are also due to science writer Tonya Clayton, for her work in condensing the scientific material into this readable overview report. The support of the Arctic countries and non-Arctic countries implementing research and monitoring in the Arctic is vital to the success of AMAP. The AMAP work is essentially based on ongoing activities within these countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the AMAP assessments. In particular, AMAP would like to thank Canada, Norway and the Nordic Council of Ministers for their financial support to the AOA work, and the sponsors of programs and projects that have delivered data for use in this assessment.

The AMAP Working Group is pleased to present this report to the Arctic Council and the wider public.

Supporting and associated documents

[1] AMAP, 2013. AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii+99pp.

[2] AMAP, 2013. Arctic Ocean Acidification Assessment: Key Findings
www.amap.no/documents/doc/amap-arctic-ocean-acidification-assessment-key-findings/809

[3] AMAP, 2013. AMAP Arctic Ocean Acidification Assessment: Summary for Policymakers
www.amap.no/documents/doc/amap-arctic-ocean-acidification-assessment-summary-for-policy-makers/808

[4] ACIA, 2005. Arctic Climate Impact Assessment. ACIA Overview report. Cambridge University Press. 1020 pp.

[5] AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii + 538 pp.

[6] Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); Climate Change 2013: The Physical Science Basis

[7] Arctic Ocean Acidification (film) *www.amap.no/documents/doc/arctic-ocean-acidification-2013-full-version/803*

*Additional sources of graphics in this report

Page 9: Pie graphs. Data from *globalcarbonproject.org*.

Page 9: Line graphs. Modified from M. Steinacher and others (2009) Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model, ***Biogeosciences*** 6:515-533, and M. Yamamoto-Kawai and others (2011) Effects of ocean acidification, warming, and melting of sea ice on Ω of Canada Basin surface water, Ecosystem Studies of Sub-Arctic Seas 2011 Open Science Meeting.

Page 12. Line graph. Modified from Doney and others (2009) Ocean acidification: The other CO_2 problem, *Annual Review of Marine Science* 1:169-192.

Page 15: Line graphic. After D. Archer (2009) *The Long Thaw: How Humans Are Changing the Next 100,000 Years of Earth's Climate*.

Mark Patsavas

CONTENTS

ARCTIC OCEAN ACIDIFICATION
EXECUTIVE SUMMARY 2013

ACIDIFICATION IN THE ARCTIC OCEAN

Key finding 1

Arctic marine waters are experiencing widespread and rapid ocean acidification

Scientists have measured significant rates of acidification at several Arctic Ocean locations. In the Nordic Seas, for example, acidification is taking place over a wide range of depths—most rapidly in surface waters and more slowly in deep waters. Decreases in seawater pH of about 0.02 per decade have been observed since the late 1960s in the Iceland and Barents Seas. Notable chemical effects related to acidification have also been encountered in surface waters of the Bering Strait and the Canada Basin of the central Arctic Ocean.

Key finding 2

The primary driver of ocean acidification is uptake of carbon dioxide emitted to the atmosphere by human activities

When carbon-rich materials such as coal or oil are burned (for example, at power stations), carbon dioxide is released to the atmosphere. Some of this gas is absorbed by the oceans, slowing its build-up in the atmosphere and thus the pace of human-induced climate warming, but at the same time increasing seawater acidity. As a result of human carbon dioxide emissions, the average acidity of surface ocean waters worldwide is now about 30% higher than at the start of the Industrial Revolution.

Key finding 3

The Arctic Ocean is especially vulnerable to ocean acidification

Owing to the large quantities of freshwater supplied from rivers and melting ice, the Arctic Ocean is less effective at chemically neutralizing carbon dioxide's acidifying effects, and this input is increasing with climate warming. In addition, the Arctic Ocean is cold, which favors the transfer of carbon dioxide from the air into the ocean. As a result of these combined influences, Arctic waters are among the world's most sensitive in terms of their acidification response to increasing levels of carbon dioxide. The recent and projected dramatic decreases in Arctic summer sea-ice cover mean that the amount of open water is increasing every year, allowing for greater transfer of carbon dioxide from the atmosphere into the ocean.

Key finding 4

Acidification is not uniform across the Arctic Ocean

In addition to seawater uptake of carbon dioxide, other processes can be important in determining the pace and extent of ocean acidification. For example, rivers, sea-bottom sediments, and coastal erosion all supply organic material that bacteria can convert to carbon dioxide, thus exacerbating ocean acidification, especially on the shallow continental shelves. Sea-ice cover, freshwater inputs, and plant growth and decay can also influence local ocean acidification. The contributions of these processes vary not only from place to place, but also season to season, and year to year. The result is a complex, unevenly distributed, ever-changing mosaic of Arctic acidification states.

BIOLOGICAL RESPONSES TO OCEAN ACIDIFICATION

Key finding 5

Arctic marine ecosystems are highly likely to undergo significant change due to ocean acidification

Arctic marine ecosystems are generally characterized by short, simple food webs, with energy channeled in just a few steps from small plants and animals to large predators such as seabirds and seals. The integrity of such a simple structure depends greatly on key species such as the Arctic cod. Pteropods (sea butterflies) and echinoderms (sea stars, urchins) are key food-web organisms that may be sensitive to ocean acidification. Too few data are presently available to assess the precise nature and extent of Arctic ecosystem vulnerability, as most biological studies have been undertaken in other ocean regions. Arctic-specific long-term studies are urgently needed.

Key finding 6

Ocean acidification will have direct and indirect effects on Arctic marine life. It is likely that some marine organisms will respond positively to new conditions associated with ocean acidification, while others will be disadvantaged, possibly to the point of local extinction

Examples of direct effects include changes in growth rate or behavior. The best-studied direct effects include effects on shell formation and organism growth: experiments show that a wide variety of animals grow more slowly under the acidification levels projected for coming centuries. Some seagrasses, in contrast, appear to thrive under such conditions. Indirect effects include changes in food supply or other resources. For example, birds and mammals are not likely to be directly affected by acidification but may be indirectly affected if their food sources decline, expand, relocate, or otherwise change in response to ocean acidification. Ocean acidification may alter the extent to which nutrients and essential trace elements in seawater are available to marine organisms.

Some shell-building Arctic mollusks are likely to be negatively affected by ocean acidification, especially at early life stages. Juvenile and adult fishes are thought likely to cope with the acidification levels projected for the next century, but fish eggs and early larval stages may be more sensitive. In general, early life stages are more susceptible to direct effects of ocean acidification than later life stages. Organisms living in environments that typically experience wide fluctuations in seawater acidity may prove to be more resilient to ocean acidification than organisms accustomed to a more stable environment.

Key finding 7

Ocean acidification impacts must be assessed in the context of other changes happening in Arctic waters

Arctic marine organisms are experiencing not only ocean acidification, but also other large, simultaneous changes. Examples include climate change (which fundamentally changes physical, chemical, and biological conditions), harvesting, habitat degradation, and pollution. Ecological interactions—such as those between predators and prey, or among competitors for space or other limited resources—also play an important role in shaping ocean communities. As different forms of sea life respond to environmental change in different ways, the mix of plants and animals in a community will change, as will their interactions with each other. Understanding the complex, often unpredictable effects of combined environmental changes on Arctic organisms and ecosystems remains a key knowledge gap.

POTENTIAL ECONOMIC AND SOCIAL IMPACTS OF OCEAN ACIDIFICATION ON ARCTIC FISHERIES

Key finding 8

Ocean acidification is one of several factors that may contribute to alteration of fish species composition in the Arctic Ocean

Ocean acidification is likely to affect the abundance, productivity, and distribution of marine species, but the magnitude and direction of change are uncertain. Other processes driving Arctic change include rising temperatures, diminishing sea ice, and freshening surface waters.

Key finding 9

Ocean acidification may affect Arctic fisheries

Few studies have estimated the socio-economic impacts of ocean acidification on fisheries, and most have focused largely on shellfish and on regions outside the Arctic. The quantity, quality, and predictability of commercially important Arctic fish stocks may be affected by ocean acidification, but the magnitude and direction of change are uncertain. Fish stocks may be more robust to ocean acidification if other stresses—for example, overfishing or habitat degradation—are minimized.

Key finding 10

Ecosystem changes associated with ocean acidification may affect the livelihoods of Arctic peoples

Marine species harvested by northern coastal communities include species likely to be affected by ocean acidification. Most indigenous groups harvest a range of organisms and may be able to shift to a greater reliance on unaffected species. Changing harvests might affect some seasonal or cultural practices. Recreational fish catches could change in composition. Marine mammals, important to the culture, diets and livelihoods of Arctic indigenous peoples and other Arctic residents could also be indirectly affected through changing food availability.

WHAT SHOULD BE DONE

What can the Arctic Council States and members do to address this serious issue for our future?

Because more than a quarter of global carbon dioxide emissions from fossil fuels come from the Arctic Council States, the Arctic Council has an opportunity to provide leadership by addressing the global ocean acidification issue. It is increasingly clear from the scientific evidence that immediate cuts in carbon dioxide emissions are essential to slow the acidification of the Arctic Ocean.

The biological, social, and economic effects of ocean acidification are potentially significant for the Arctic nations and their peoples, as well as global society. Effects on the marine ecosystems and northern societies due to ocean acidification are likely to have significant impacts, particularly on future fisheries and potentially on harvesting of marine mammals and marine tourism. There remain large gaps in knowledge that currently prevent reliable projections of these impacts.

Based on the key findings from the Arctic Ocean Acidification scientific assessment, the AMAP Working Group agreed to the following recommendations:

IT IS RECOMMENDED THAT THE ARCTIC COUNCIL

1. Urge its Member States, Observer countries, and the global society to reduce the emission of carbon dioxide as a matter of urgency.
2. Call for enhanced research and monitoring efforts that expand understanding of acidification processes and their effects on Arctic marine ecosystems and northern societies that depend on them.
3. Urge its Member States to implement adaptation strategies that address all aspects of Arctic change, including ocean acidification, tailored to local and societal needs.

Peter Prokosch

THE KIRUNA DECLARATION: RESPONDING TO OCEAN ACIDIFICATION

In spring 2013, the key findings of the 2013 AMAP Arctic Ocean Acidification assessment and the associated recommendations of the AMAP Working Group were presented at the Kiruna Ministerial Meeting in Sweden.

In response, the Arctic Ministers approved the AMAP Arctic Ocean Acidification assessment and the recommendations from the Working Group.

The Kiruna Declaration, signed on 15 May 2013 by the ministerial representatives of the Arctic Council, includes the following:

> *“We, the Ministers representing the eight Arctic States, joined by the representatives of the six Permanent Participant organizations of the Arctic Council, have gathered in Kiruna, Sweden, at the conclusion of the first cycle of Chairmanships for the Eighth Ministerial meeting of the Arctic Council, … hereby …*
>
> ***Welcome** the Arctic Ocean Acidification assessment, **approve** its recommendations, **note** with concern the potential impacts of acidification on marine life and people that are dependent on healthy marine ecosystems, **recognize** that carbon dioxide emission reductions are the only effective way to mitigate ocean acidification, and **request** the Arctic States to continue to take action on mitigation and adaptation and to monitor and assess the state of Arctic Ocean acidification, …”*

Goddard Space Flight Center, and ORBIMAGE

Sea ice in the Labrador Sea

THE LANGUAGE OF OCEAN ACIDIFICATION

The language of ocean acidification may at first seem confusing. Here are a few basic terms:

Hydrogen ions are found in seawater, blood, and most liquids. Seawater chemistry and many biological processes are responsive to hydrogen ions. The symbol for hydrogen ions is H^+.

Acidity is a measure of *how many* hydrogen ions are in a given volume of liquid. A cup of lemon juice has a higher acidity (contains more hydrogen ions) than a cup of black coffee. Today's ocean-surface water has a higher acidity than pre-industrial surface water.

One way to conveniently express acidity is in terms of **pH**.[1] The greater a liquid's acidity, the lower its pH. A small change in pH is equivalent to a large change in acidity. The average pH of the world's ocean-surface waters is now about 8.1.

Acidification refers to an *increase* in the number of hydrogen ions in a given volume of liquid. We can acidify a glass of tap water by adding lemon juice.

Ocean acidification is a *progressive increase* in the acidity of ocean waters over an extended period, typically decades or longer. We are currently acidifying the oceans by adding large amounts of carbon dioxide.

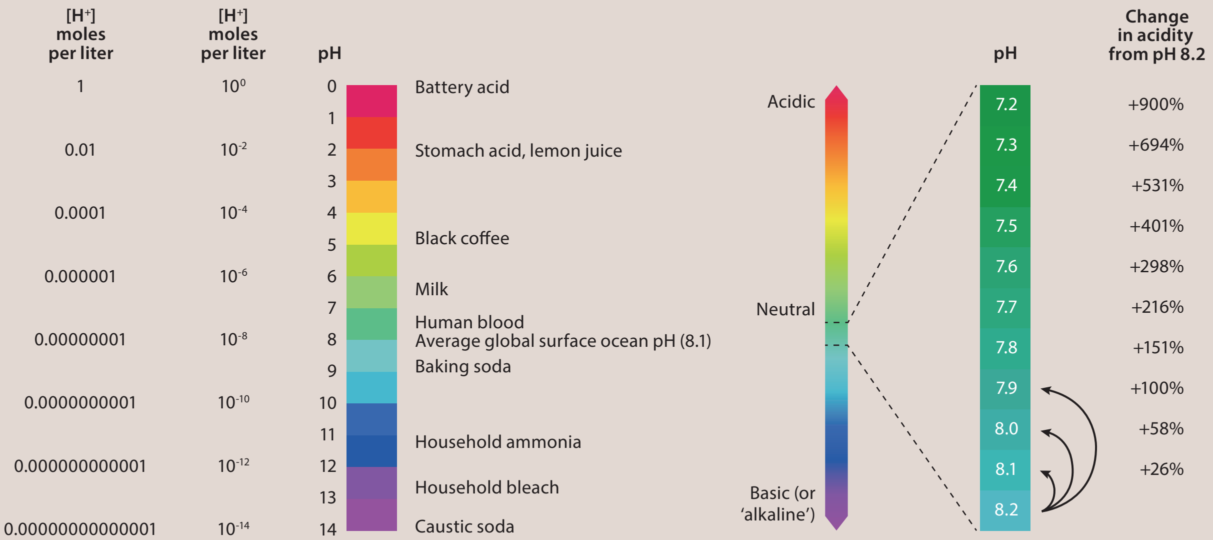
'**Acidic**' is a term used to describe liquids that contain more than a certain number of hydrogen ions. Liquids with a pH less than 7 are labeled 'acidic'. Milk is mildly acidic, and battery acid is strongly acidic. Typical seawater is not acidic.

'Corrosive,' in the context of ocean acidification, usually refers to waters capable of dissolving ***aragonite,*** a form of calcium carbonate (a mineral) used by some marine organisms to build their shells or skeletons. Aragonite-corrosive seawater does not dissolve other materials such as seagrass blades, fish scales, or human skin.

Global *ocean acidification* is happening now. Since pre-industrial times, the acidity of ocean-surface water has increased by about 30 %.[2]

Scientists do not expect that ocean acidification will lead to an overall *acidic* ocean. Some ocean waters may cross the 'acidic' threshold (pH 7) during some times of the year, but most ocean waters will not. Even if we were to burn all of the Earth's fossil fuels, we would not produce an overall acidic ocean.

Scientists are concerned about the ecological consequences of rapidly increasing *acidity*. In Earth's ancient past, many species have gone extinct in association with episodes of ocean acidification. Today's acidification is happening at a fast pace. In addition, today's acidification is accompanied by many other large-scale changes in Earth's climate, chemistry, and biology (for example, increasing temperatures and decreasing sea ice). Social and economic changes (for example, urbanization and new fishing technologies) are also affecting the oceans. This unusual combination of rapidly changing conditions may pose a particular challenge to marine life.



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[1] Expressed mathematically: $pH = -\log[H^+]$, where the symbol $[H^+]$ represents the concentration of hydrogen ions.

[2] According to the IPCC Working Group I report, the pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26 % increase in hydrogen ion concentration.

OCEAN ACIDIFICATION
IS AN ARCTIC ISSUE

ARCTIC MARINE WATERS ARE EXPERIENCING WIDESPREAD AND RAPID OCEAN ACIDIFICATION.
OCEAN ACIDIFICATION WILL AFFECT ARCTIC MARINE LIFE

The Arctic way of life is changing.
Air and ocean temperatures are rising. Sea ice and land ice are melting. Runoff is increasing. Permafrost is thawing. Arctic shores are eroding. Fishing and hunting practices are changing.

A less obvious but profound change is occurring within the sea: **The acidity of our ocean waters is increasing faster now than ever before in human history.**

This change is important because acidity[1] strongly influences many chemical and biological processes important to plant, animal, and human well-being. The chemical make-up of seawater today is significantly different than just two centuries or even two decades ago. The pace of change is likely to be faster now than at any other time during the past 55 million years.

Measurements show that **seawater acidity is increasing** in the Arctic Ocean[2] and worldwide. This type of chemical change – a widespread and ongoing increase in seawater acidity – is known as *ocean acidification*.

Compared to other oceans, the **Arctic is especially sensitive** to acidification. This sensitivity and the mounting evidence for acidification of Arctic marine waters are explained further on pages 4 to 7.

The primary **cause** of ocean acidification is the same as the primary cause of recent Arctic warming and ice melt: namely, the growing inventory of **carbon dioxide** in the Earth's atmosphere.

Much of this carbon dioxide enters the oceans, and the chemical result is ocean acidification. Local processes, including Arctic climate change, can also influence carbon dioxide levels in seawater. More detail on the carbon-dioxide and climate-change connections to Arctic Ocean acidification may be found on pages 8 to 11.

The **biological effects** of ocean acidification are much more difficult to assess than the chemical effects. Certainly, many of today's Arctic marine plants and animals live immersed in seawater of significantly higher acidity than earlier generations. Equally certain is the fact that future generations will live in seawater of yet higher acidity. The current patchwork of Arctic Ocean acidification and current and future trends is discussed on pages 12 to 15.


Pernilla Carlsson

Laboratory experiments and field observations indicate a wide range of plant and animal responses to ocean acidification. Some organisms respond negatively, and some respond positively. Some exhibit no direct response. Some of these findings are more certain than others, and some are better understood than others. Scientific findings relevant to the effects of ocean acidification on different types of Arctic plants and animals are reported on pages 16 to 19.

Because ocean acidification is happening at the same time as other major Arctic changes (for example, ocean warming and sea-ice melting and decline), teasing out or predicting the effects of any one factor is difficult. What can be said is that Arctic **marine ecosystems** are vulnerable to ocean acidification. The reasons for this are outlined on pages 20 to 21.

Assessing **potential impacts to humans** is especially challenging. Much is still unknown about the implications of ocean acidification for marine life, and adding in considerations of human behavior and economics makes the tangle all the more complex. Some expert speculations and preliminary findings regarding the social and economic consequences of Arctic Ocean acidification are presented on pages 22 to 24.

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[1] For an explanation of 'acidity' and related terms, see page 1.

[2] In this report, the term 'Arctic Ocean' refers not only to the central Arctic Ocean basin but also to its marginal seas.

THE SPECIAL CASE OF **ARCTIC VULNERABILITY**

IN TERMS OF ACIDIFICATION RESPONSE, ARCTIC OCEAN WATERS ARE AMONG THE WORLD'S MOST SENSITIVE

Prior AMAP assessments have shown that the Arctic is **especially sensitive** to impacts from a wide range of global human activities. Ocean acidification is no exception.

The Arctic Ocean is essentially a high-latitude estuary that straddles the North Pole and is surrounded on all sides by land**.** This circumstance gives the Arctic Ocean its special character – including a particular vulnerability to carbon-dioxide invasion and the impacts of ocean acidification.

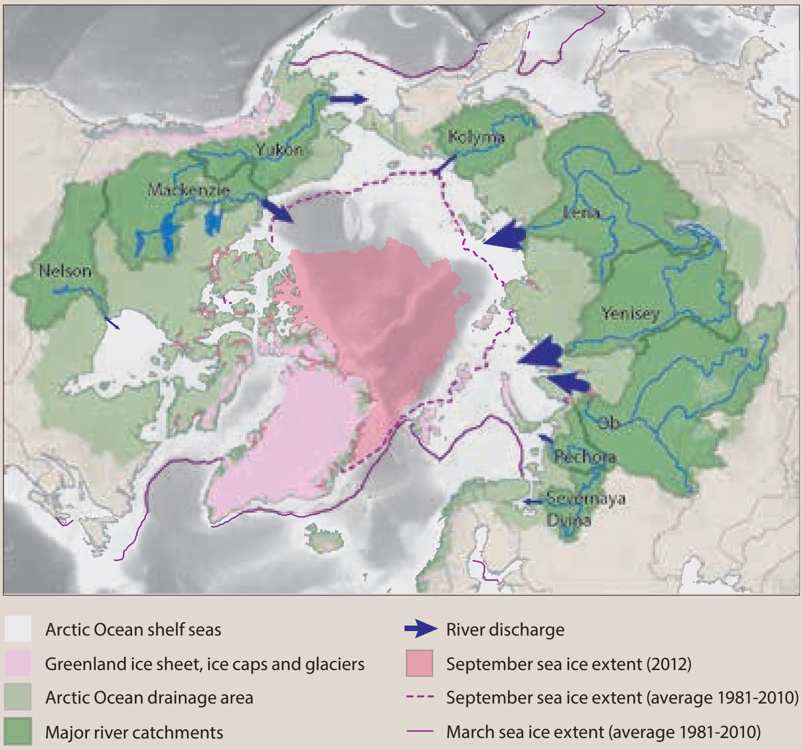
- The Arctic Ocean is **cold,** which favors the transfer of carbon dioxide from the air into the ocean.
- The Arctic Ocean receives large quantities of **fresh water** from rivers and melting ice. Less-salty seawater is not as effective as saltier seawater at chemically neutralizing the acidifying effects of carbon dioxide. Freshwater dilution also diminishes the availability of some essential components of certain types of shells and skeletons.

Some additional points of Arctic Ocean vulnerability:

- Arctic **sea-ice** cover is diminishing. As the permanent ice cover shrinks, increasingly large ocean areas are exposed to the carbon dioxide-rich atmosphere.
- Rivers, coastal erosion, and subsea permafrost supply large quantities of carbon-containing **organic material** to the sea. Marine bacteria can convert this once-living material to acidifying carbon dioxide.
- **Deep waters** naturally high in acidity well up from the ocean depths onto some outer shelves. Some upwelled waters can be corrosive[1] to bare shells that lack a protective coating.
- **Methane** gas seeps from the sea bottom in some shelf areas. This carbon-rich gas can react with oxygen to form carbon dioxide.
- **Arctic ecosystems** are characterized by low biodiversity and simple food webs. This structure is more susceptible to disruption than are more complex arrangements.
- Arctic marine organisms are experiencing not only rapid ocean acidification but also **other major environmental changes.** For example, sea-ice cover is declining and surface waters are becoming appreciably warmer and less salty.
- Indigenous Arctic peoples depend heavily on **traditional foods** harvested from the local environment. This dependence makes local communities potentially vulnerable to decreases in traditional food harvests. Such changes may have spiritual and cultural implications.

Owing to the combined influences of increasing carbon dioxide and climate warming, the Arctic Ocean is among the **world's first** to exhibit large areas of '**corrosive**' surface and near-surface waters – that is, waters capable of dissolving some common forms of shell material. Scientists expect the corrosive zones to expand in coming years.

▼ The Arctic Ocean contains only 1 % of the global ocean volume but receives about 11 % of global river discharge. The Arctic's enormous continental shelves account for half of the Arctic's ocean area. On this map, the larger the arrows are, the greater the river discharge.



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[1] For an explanation of this use of the term 'corrosive', see page 1.

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THE EVIDENCE FOR ARCTIC OCEAN ACIDIFICATION

The Arctic Ocean is a difficult place for scientists to work. For this reason, Arctic seawater measurements are infrequent and widely scattered compared to other ocean areas. Wintertime data are especially scarce.

Nevertheless, the growing body of evidence gives a clear message: **rapid acidification** is occurring in the Arctic Ocean and its influence is **spreading**.

OCEAN ACIDIFICATION

The term *ocean acidification* refers simply to an increase in seawater acidity over an extended period of time, typically decades or longer. Some ocean acidification occurs naturally. *Anthropogenic ocean acidification* refers to the portion of acidity increase that is caused by human activity.

Significant **global ocean acidification** is happening now**.** Today's ocean acidification is:

- Happening **fast** – likely faster than at any other time during the past 55 million years.
- The **first occurrence in human history.**
- **Caused by humans.**

The primary cause of modern ocean acidification is the carbon dioxide released by humans burning fossil fuels. This driving force and other contributors are discussed in more detail on pages 8 to 11.

SCIENTISTS HAVE DOCUMENTED SIGNIFICANT OCEAN ACIDIFICATION IN ARCTIC MARINE WATERS

Ocean acidification is a concern because (a) seawater acidity influences a great many chemical reactions that are important to sea life, and (b) ocean acidification is occurring most strongly in the upper ocean, where most marine life dwells. Some of the biological concerns regarding ocean acidification are outlined on pages 16 to 21.

Scientists have measured the signs of ocean acidification in many locations around the globe, including the Arctic Ocean. The Arctic Ocean is in fact on the forefront of this dramatic chemical change.

Observations of increasing seawater acidity

Some of the clearest evidence for Arctic Ocean acidification comes from the Iceland and Norwegian Seas. Repeated measurements show a trend of rapidly increasing acidity (that is, declining pH) in surface waters in recent years. Historical data suggest a similar three-decade trend in the Barents Sea.

In some areas, ocean waters show large fluctuations in acidity but no obvious overall trend. The Bering Sea and the surface waters of the Greenland Sea are examples. Long-term trends can be difficult to detect in regions where sampling is intermittent.

Acidification is strongest in surface waters, but depending on the direction of ocean flow, its reach may extend to deeper waters.

Acidification is evident, for example, in the deep waters of the Iceland Sea. The pace of change in these quiet dark waters is slower than in the waters closer to the ocean’s surface.

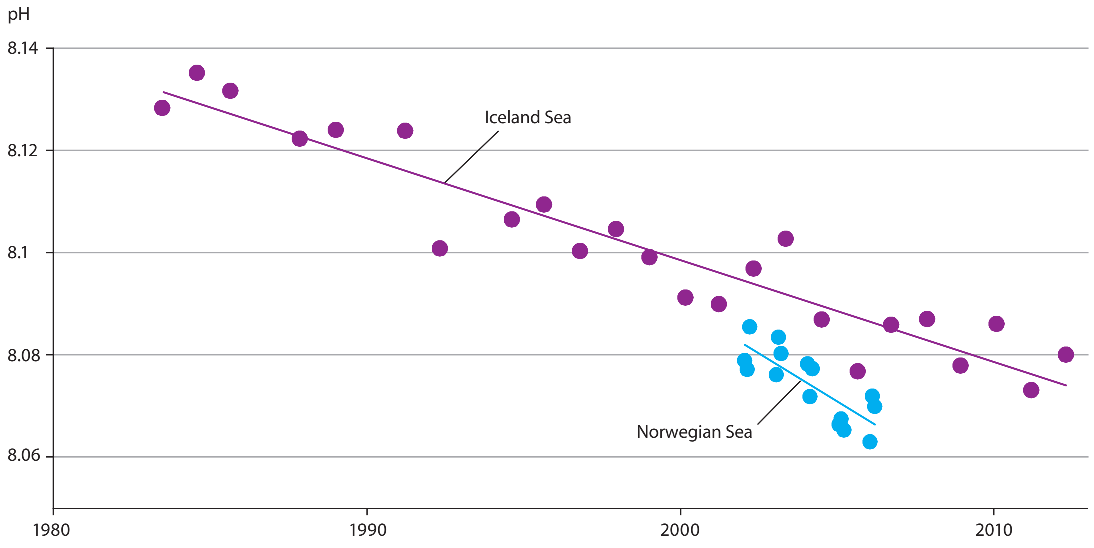
These Arctic trends are consistent with measurements made at many places around the globe in recent decades.

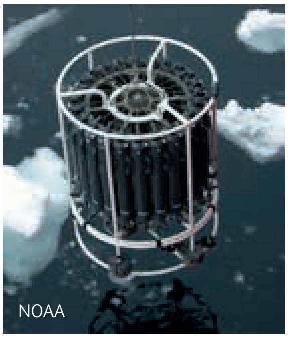
▶▶ Observed pH and aragonite saturation states in Arctic seas. Lower pH indicates higher acidity. A saturation state lower than 1.0 indicates waters corrosive to aragonite.

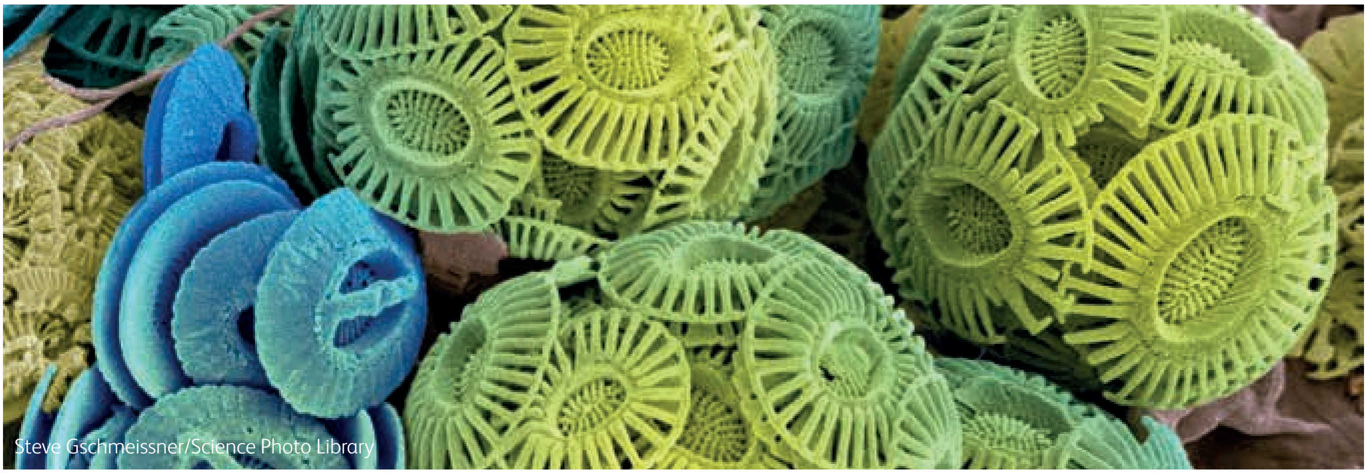
Region	pH	Aragonite saturation state
Nordic seas		
Surface	8.1–8.4	1.5–3.5
Bottom	7.9–8.3	0.7–2.2
Bering Sea		
Surface	7.9–8.3	0.7–2.9
Bottom	7.0–7.7	0.1–2.0
Siberian Shelves		
Surface[a]	7.5–8.1	0.2–2.5
Bottom	7.4–7.9	0.2–1.4
Chukchi & Beaufort shelves		
Surface	7.9–8.4	0.8–2.0
Bottom	7.8–8.1	0.8–2.0
Canadian Archipelago		
Surface	8.0–8.3	0.8–2.2
Bottom	7.6–8.1	0.6–1.4
Central Arctic		
Surface	8.0–8.2	1.3–1.8
Deeper than 2000 m	~8.1	0.6–1.0

[a] Includes data from close to river mouths.

▶ Some Arctic surface waters have increased in acidity (as indicated by declining pH) in recent years.






Steve Gschmeissner/Science Photo Library

▲ Many Arctic organisms manufacture ***calcium carbonate*** to build their shells or skeletons.

ARAGONITE SATURATION STATE

The most direct way to look at ocean acidification is through repeated measurements of seawater acidity. Another way is through assessments of *calcium carbonate saturation state.*

Calcium carbonate is a mineral manufactured by many Arctic organisms to build shells or skeletons. The saturation state is a number that describes the chemical propensity of seawater to form or dissolve calcium carbonate.

Ocean acidification depresses calcium carbonate saturation states. So do additions of fresh water or organic material. Such additions may be provided by melting sea ice or inflowing rivers.

Low saturation states seem to present a challenge to some, but not all, plants and animals that manufacture calcium carbonate. Very low saturation states indicate seawater that is capable of dissolving calcium carbonate.

In the Arctic, scientists are paying particular attention to **aragonite saturation state** because aragonite is a widely used and relatively vulnerable form of calcium carbonate. Examples of Arctic organisms that manufacture aragonite are pteropods (sea butterflies) and corals.

Waters with an aragonite saturation state of less than 1.0 are said to be **'corrosive'** – capable of dissolving aragonite shells and skeletons that are not protected from contact with the seawater (for example, by a protective coating). Examples of Arctic saturation-state values are shown in the table on page 6.

In recent years, researchers have found **declining aragonite saturation states** and **expanding corrosive zones** at several places around the globe, including the Arctic Ocean.

Observations of increasing corrosion potential

Some of the most striking Arctic changes are being seen in the Canada Basin. Scientists who surveyed this area in 1997 found no corrosive surface waters, but subsequent visits in 2008 and later showed that surface waters had become extensively corrosive. The Canada Basin was the first deep ocean area where scientists found surface waters to be corrosive over a wide area.

In the Iceland Sea, aragonite saturation states are rapidly declining in concert with increasing acidity. Substantial areas of seafloor are transitioning from non-corrosive to corrosive conditions.

Scientists have also found corrosive waters at or near the sea surface in the Laptev and eastern East Siberian Seas, on the Chukchi and Beaufort shelves, and in the Canadian Archipelago. In the Chukchi and Bering Seas, naturally corrosive subsurface waters sometimes flow up to the surface zone of biological activity.

Even without human influence, Arctic saturation states are relatively low. The bottom waters of the East Siberian and Bering seas, for example, are naturally corrosive. Some bottom waters of the Barents Sea are nearly corrosive.

The Arctic Ocean is a **global standout** in terms of its combination of low and declining aragonite saturation states. Surface waters and shelf waters are poised for further declines through human influence.

Scientists expect the Arctic Ocean to be the **first** ocean region to achieve persistently widespread corrosive surface waters – this is likely to occur within the next few decades, well within the lifetimes of today's young adults and children.

THE CAUSES OF ARCTIC OCEAN ACIDIFICATION

HUMAN EMISSIONS OF CARBON DIOXIDE TO THE ATMOSPHERE ARE THE MAJOR DRIVING FORCE BEHIND OCEAN ACIDIFICATION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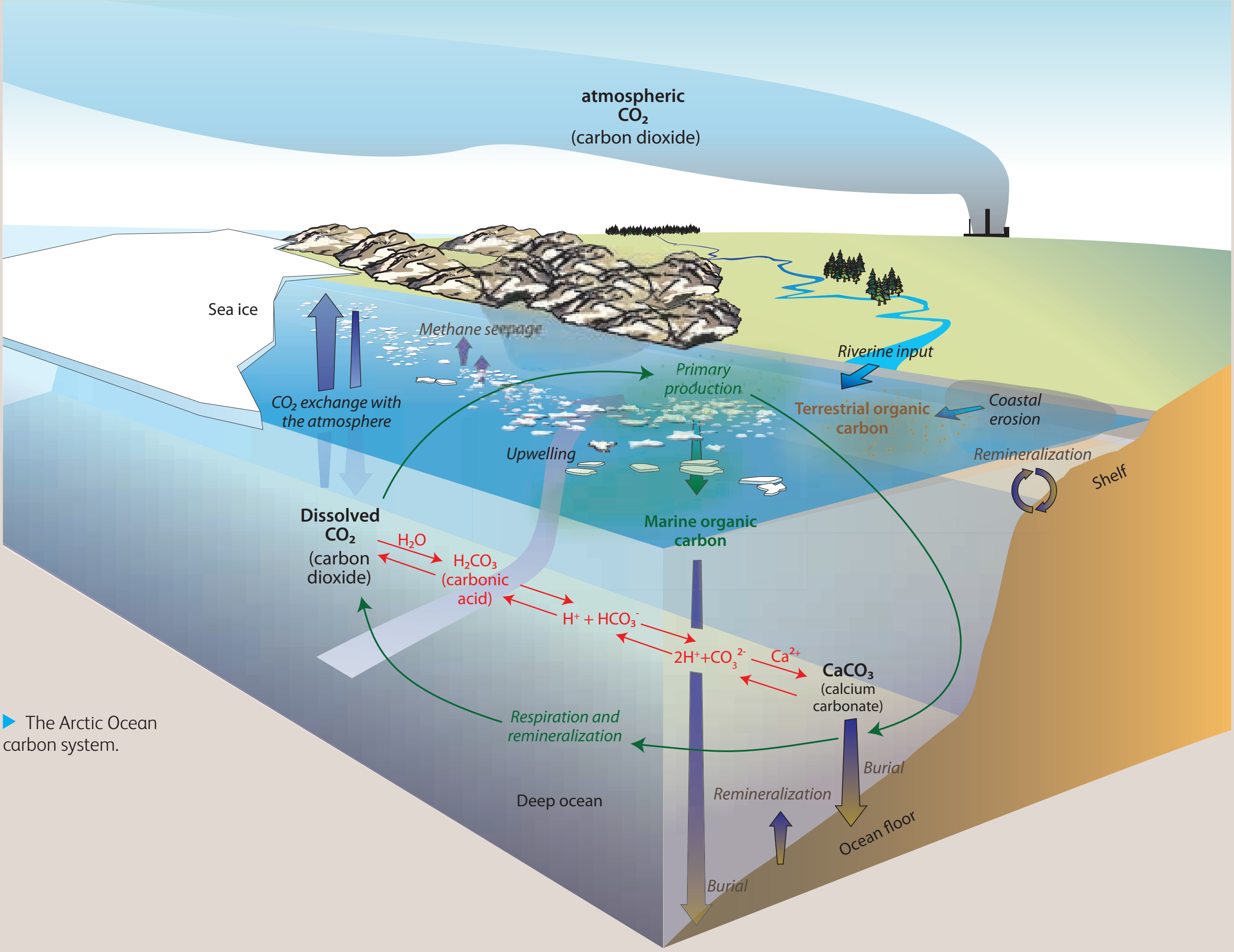
The major driving force behind ocean acidification, both globally and in the Arctic Ocean, is seawater uptake of carbon dioxide that humans emitted to the atmosphere. As atmospheric carbon dioxide has climbed (see graph on page 12), so has the acidity of the upper ocean.

Other processes that involve carbon dioxide play a role too. Climate change is acting to exacerbate Arctic Ocean acidification and its impacts.



▶ The Arctic Ocean carbon system.

THE CARBON DIOXIDE CONNECTION: FROM EARTH TO AIR TO SEA

The amount of **carbon dioxide** in the **atmosphere** has increased by approximately 40 % since pre-industrial times. The sharpest increases have occurred in recent decades.

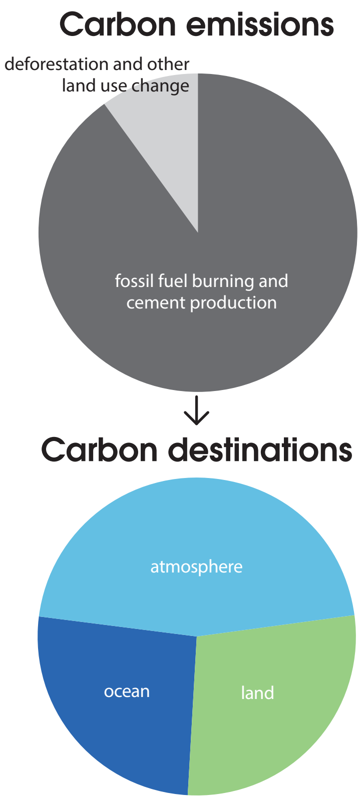
Most of today's carbon emissions come from **fossil fuel burning** and cement production (90 %). Land use changes such as deforestation contribute a smaller fraction (10 %).

The **oceans** are currently **absorbing** about one quarter of present-day emissions. In essence, humans are transferring fossil-fuel carbon from beneath the earth (by mining and drilling and then combustion) to the oceans via the atmosphere.

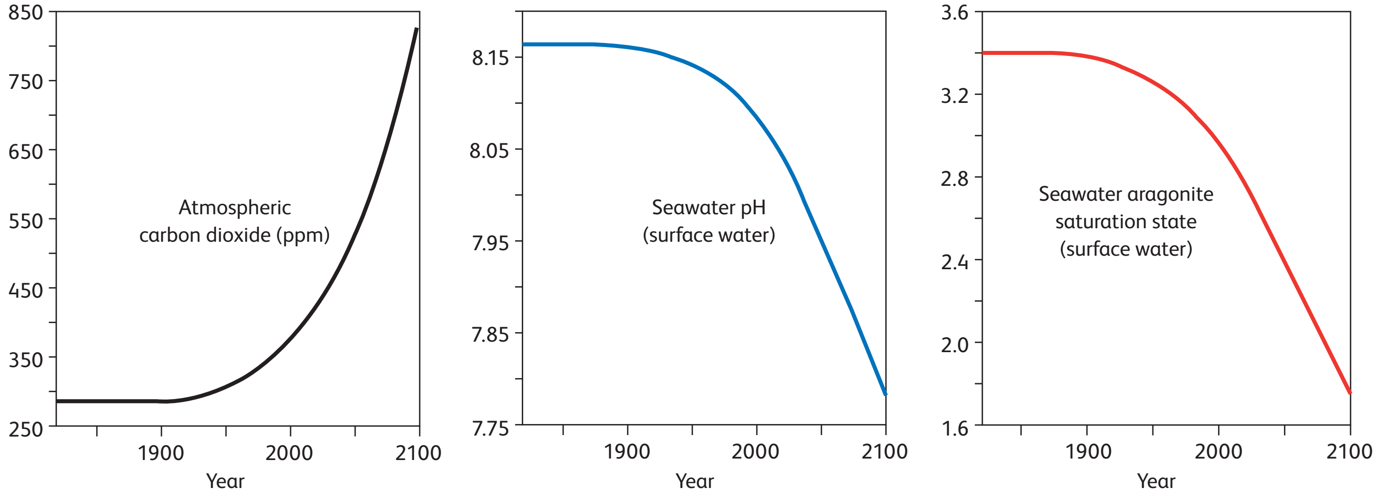
By removing heat-trapping carbon dioxide from the atmosphere, the oceans help to slow human-caused global warming. This valuable ecological service, though, has consequences for seawater chemistry and marine life.

The effect on seawater chemistry has been profound. Global average **surface-ocean acidity** has **increased** approximately 30 %[1] since pre-industrial times, and areas of **aragonite-corrosive seawater** are **expanding**.

The effect on marine life is more difficult to document.



▼ Simulated ocean response to increased atmospheric carbon dioxide emissions.

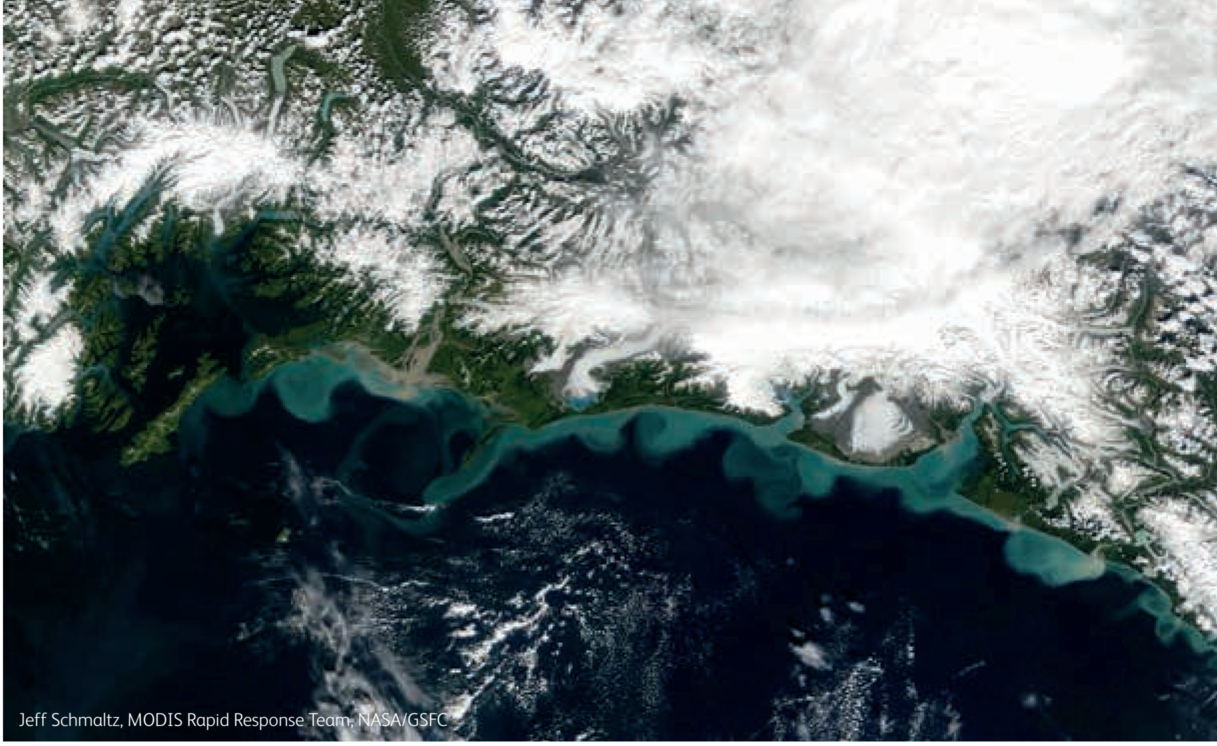


THE MANY FACES OF CARBON DIOXIDE

Adding carbon dioxide to seawater has chemical and biological consequences:

- **Carbon dioxide increases.** Increasing carbon dioxide in seawater typically changes the internal body chemistry of ectothermic ('cold-blooded') animals. Most marine animals are ectotherms; birds and mammals are not. Seagrasses use carbon dioxide for photosynthesis.
- **Acidity increases.** Many marine animals grow more slowly when subjected to the acidity levels projected for coming centuries. Examples include clams, scallops, and urchins.
- **Dissolved bicarbonate increases.** This increase is slight. Some marine algae use this ion for photosynthesis.
- **Dissolved carbonate decreases.** Low abundance of this ion contributes to increased risk of dissolution for aragonite and other forms of the mineral calcium carbonate.

[1] According to the IPCC Working Group I report, the pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26 % increase in hydrogen ion concentration.



Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC

Other carbon dioxide processes

The **addition of carbon dioxide** to seawater, from whatever source, directly increases (↑) seawater acidity. The **removal of carbon dioxide**, by whatever process, decreases (↓) seawater acidity.

	Effect on seawater carbon dioxide	Effect on seawater acidity	Effect on seawater aragonite saturation state
Ocean uptake of atmospheric carbon dioxide	↑	↑	↓
Photosynthesis	↓	↓	↑
Decay of plant or animal remains (remineralization)	↑	↑	↓
Respiration	↑	↑	↓
Methane reaction with oxygen	↑	↑	↓
Formation of aragonite (and other forms of calcium carbonate)	↑	↑	↓
Dissolution of aragonite (and other forms of calcium carbonate)	↓	↓	↑

Photosynthesis removes carbon dioxide from seawater in the sunlit upper ocean. **Respiration** and **decay** add carbon dioxide. Because deep ocean waters lie beyond the reach of sunlight (hence no photosynthesis; only respiration and decay), they are naturally rich in carbon dioxide and high in acidity. At high latitudes, a brief but strong spring/summer pulse of phytoplankton growth (↓seawater acidity) in the newly sunlit upper ocean is sometimes followed by a strong autumn pulse of decay (↑acidity) at depth.

Methane gas can react with oxygen to form carbon dioxide. In some Arctic shelf areas, methane leaks from the seabed due to natural long-term shelf flooding and warming in the wake of the last Ice Age. Methane effects are therefore exhibited most strongly in shelf bottom waters.

Calcium carbonate formation increases the carbon dioxide content of seawater. In the ocean, most of this mineral formation occurs in sunlit upper-ocean waters. **Calcium carbonate dissolution** decreases the carbon dioxide content of seawater. In the ocean, most dissolution occurs in deeper zones, after shelled organisms die and sink into the dark, corrosive waters.

Nutrients can indirectly influence seawater acidity. Under the right conditions (including sufficient sunlight, for example), fertilizing elements such as nitrogen or phosphorus can stimulate upper-ocean photosynthesis. Much of the newly produced organic material eventually sinks and decays.

Arctic rivers (page 4) are an important supplier of nutrients. Near the outer edge of the continental shelves, a source of nutrients and also carbon dioxide is the intermittent upward flow of seawater. Such upwelling events may bring nutrient-rich waters up into the sunlit zone, thus kicking off another photosynthesis/decay cycle.

Terrestrial **organic carbon** (biological material) can also indirectly influence seawater acidity. Arctic rivers deliver large loads of organic carbon to the shelves, where marine microbes may degrade and convert some of this once-living material to carbon dioxide. Coastal erosion also supplies organic carbon. Thawing seabed permafrost is another source.

The geographical implications of these various processes are discussed on pages 12 and 13.

THE CLIMATE CHANGE CONNECTION: WARMING, FRESHENING, AND MORE

Major **climate-change** impacts relevant to Arctic Ocean acidification include**:**

- Sea-ice retreat.
- Increasing supplies of fresh water and organic carbon.

The Arctic Ocean is the **one place** on Earth where these forces have come together on such a grand scale to intensify the acidification driven by atmospheric carbon dioxide.

The Arctic region is warming, and **ice is turning to water.** Glaciers and snows are melting, and permafrost is thawing. River runoff is increasing. Sea ice is disappearing. More snow and rain may be falling.

Adding fresh water to the ocean:

- Increases ocean sensitivity to carbon dioxide. Addition of carbon dioxide to dilute seawater evokes a larger acidity increase than an addition to full-strength seawater.
- Drives down saturation states for aragonite and other forms of calcium carbonate. Freshwater dilution generally decreases the abundance of both dissolved calcium and carbonate in seawater.
- Enhances ocean stratification. A strongly layered upper ocean resists the vertical mixing that often brings nutrient-rich waters up from below; stable surface layers are therefore more susceptible to nutrient depletion.

Melting sea ice (as opposed to land ice) also:

- Exposes more sea surface to the carbon dioxide-rich atmosphere. The cold, newly exposed seawater is typically able to quickly absorb large quantities of carbon dioxide from the air.
- Encourages shelf-edge upwelling. As the ice edge retreats beyond the outer continental shelf margin, conditions become more favorable for the welling up of high-acidity, nutrient-rich seawater from ocean depths.

Eroding coastal shorelines:

- Supply large quantities of organic carbon to shelf waters. Marine microbes may convert this carbon, which was once stored in shoreline soils, lichens, or plants, to carbon dioxide.

Thawing permafrost, on land and especially at the sea bottom:

- Supplies large quantities of organic carbon to shelf waters. Microbes can then convert the once-living carbon to carbon dioxide.

Warming of seawater:

- Slows the entry of carbon dioxide into the ocean. Warmer seawater holds less carbon dioxide than colder seawater.
- Increases calcium carbonate saturation states. This effect is important globally, but in the Arctic, freshwater depression of saturation states is more significant at present.
- May release methane from shelf sediments. Such an event would exacerbate seawater acidification and diminish seawater oxygen.

Climate change also affects marine **primary production** (photosynthesis) but in complicated ways. The net effect is unclear and probably differs from place to place.

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ARCTIC VARIABILITY: AN EVER-CHANGING MOSAIC

ACIDIFICATION IS NOT UNIFORM ACROSS THE ARCTIC OCEAN

The Arctic Ocean does not behave as a unified whole. Different acidification-related processes dominate in different regions and at different times. The result is a complex, ever-changing mosaic of acidities and acidification vulnerabilities.

TEMPORAL VARIABILITY: FLUCTUATIONS ON A TREND

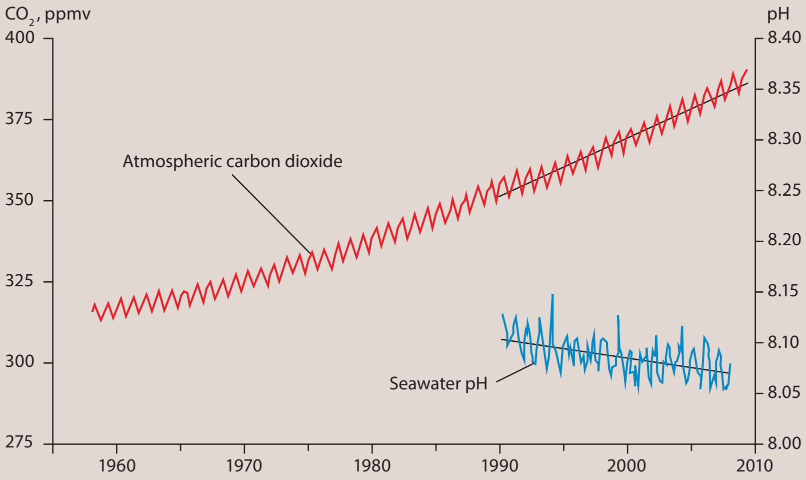
Temporal (through-time) variability occurs over a range of scales, short and long. In shallow coastal waters, for example, daytime acidity can be significantly lower than night-time acidity due to light-driven cycles of photosynthesis and respiration (see table on page 10).

Substantial seasonal changes may also occur. The burst of springtime productivity that comes with the return of sunlight after the long Arctic winter can substantially decrease seawater acidity.

Such day-to-day, season-to-season, and year-to-year **fluctuations** are **superimposed on a steady long-term trend** of progressively increasing seawater carbon dioxide and acidity (declining pH). This pattern can be seen in long-term data sets from around the globe. Over time, the natural ups and downs of acidity and saturation state are more likely to reach into ranges that challenge some marine organisms.

Temporal variability is especially large on the vast Arctic shelves. The deep ocean, in contrast, is relatively stable. This difference may be important for how different organisms cope with ocean acidification. Coastal and nearshore species are already accustomed to wide fluctuations in environmental conditions – for example, temperature, salinity, and acidity – and may therefore prove to be resilient to ocean-acidification impacts.

▼ As carbon dioxide in the atmosphere increases, ocean-surface pH decreases (acidity increases). Short-term fluctuations are imposed on the long-term trends. Data from North Pacific Ocean in the vicinity of Hawaii, USA.



SPATIAL VARIABILITY: AN ARCTIC PATCHWORK

Inflow seas

The **Nordic Seas** are undergoing rapid acidification. These waters efficiently take up atmospheric carbon dioxide due to their cold temperatures and intense photosynthesis. In addition, their chemical composition is highly responsive to carbon dioxide. Deep vertical mixing transports carbon-rich waters from the surface ocean to deeper waters. In the Iceland and Norwegian Seas, surface-water acidities have risen measurably in recent years (page 6). In the Iceland Sea, substantial seafloor areas are transitioning to corrosive conditions. Limited data from the surface waters of the Greenland Sea reveal no obvious trend.

In the **Barents Sea**, little uptake of atmospheric carbon dioxide seems to occur. Nevertheless, the signal of human-generated carbon is likely to be strong here due to supply via seawater flowing in from other areas. Some bottom waters are in a nearly corrosive state. With ongoing global production of atmospheric carbon dioxide and possible local intensification of photosynthesis and decay, parts of this biologically and economically important area could become corrosive to aragonite in the near future.

The **Bering Sea**, one of the world's most productive ocean regions, is an important source of corrosive waters to the Arctic Ocean. Cold, aged Pacific waters rich in carbon dioxide flow in through the Bering Strait. Within the Bering Sea, high-carbon dioxide waters frequently well up from the depths to the ocean surface. Intensive spring/summer photosynthesis removes carbon dioxide from the upper waters, thus mitigating surface acidification. Consumption and decay of sinking biological remains, however, exacerbate acidification at depth. Patchy and infrequent sampling and naturally large seasonal swings in ocean chemistry make it difficult to quantify acidification trends in this region.

Shelf seas

Owing to organic-carbon supply from rivers and coastal erosion, surface-ocean acidity values are generally greater near the coasts than over the deep Arctic basin.

Tor Ivan Karlsen

On the **Siberian shelf**, ocean waters flow in from the Atlantic and Pacific, while rivers bring fresh water. The rivers, coastal erosion, and thawing subsea permafrost all contribute to a rich supply of organic matter. In surface waters, strong photosynthesis removes carbon dioxide, while abundant fresh water serves to amplify acidification impacts. At the sea floor, large amounts of methane seep from the sediments. Siberian shelf bottom waters are strongly corrosive to aragonite.

The **western Arctic (Chukchi and Beaufort) shelves** are strongly influenced by the inflow of North Pacific water, which is naturally high in acidity. Summertime phytoplankton growth seasonally depresses surface-water acidity, while sinking and decay of the biological remains serves to increase subsurface acidity. Even without human influence, this area is one of relatively high seawater acidity.

The **Canadian Arctic Archipelago** serves as a throughway for waters flowing from the Beaufort Sea toward the Labrador Sea. Along the way, the water's naturally high acidity increases further due to freshwater additions and organic-matter processing and decay. Scientists have found surface and near-surface waters corrosive to aragonite in Coronation Gulf and Hudson Bay.

Central Arctic basin

The **central Arctic Ocean** receives its cold surface waters largely from the surrounding shelves. These waters have a naturally high acidity, which is heightened by the addition of human-released carbon dioxide. The Canada Basin was one of the first deep-ocean areas where scientists found corrosive waters at the sea surface. The deep waters of the Arctic basin are naturally high in carbon dioxide, and waters below about 2500 meters depth are corrosive. The central Arctic Ocean has been largely insulated from natural and anthropogenic ocean acidification, but this area is likely to be more strongly impacted in the future.

LOOKING TO **THE FUTURE**

ARCTIC OCEAN SURFACE-WATER ACIDITY WILL CONTINUE TO INCREASE

Observations over the past two decades suggest that on a basin-wide scale, Arctic ocean **surface-water acidity** will **continue to increase** so long as atmospheric carbon dioxide increases.

This general trend will be modified by many factors, including ocean circulation and sea-ice formation and retreat. Some of these processes accentuate the effects of ocean acidification, while others lessen its impacts.

All of these processes are subject to great natural variability. Many are now changing also in response to human influences and a changing climate.

As a result of this complexity, the exact timing and patterns of future Arctic Ocean acidification are difficult to project. Scientists are, however, confident in their expectation of overall increasing acidity in the event of increasing atmospheric carbon dioxide.

General simulations of **future conditions** project that among all the world's ocean areas, Arctic Ocean surface waters will experience:

- The **greatest** increases in acidity.
- The **earliest** widespread occurrence of aragonite-corrosive conditions.

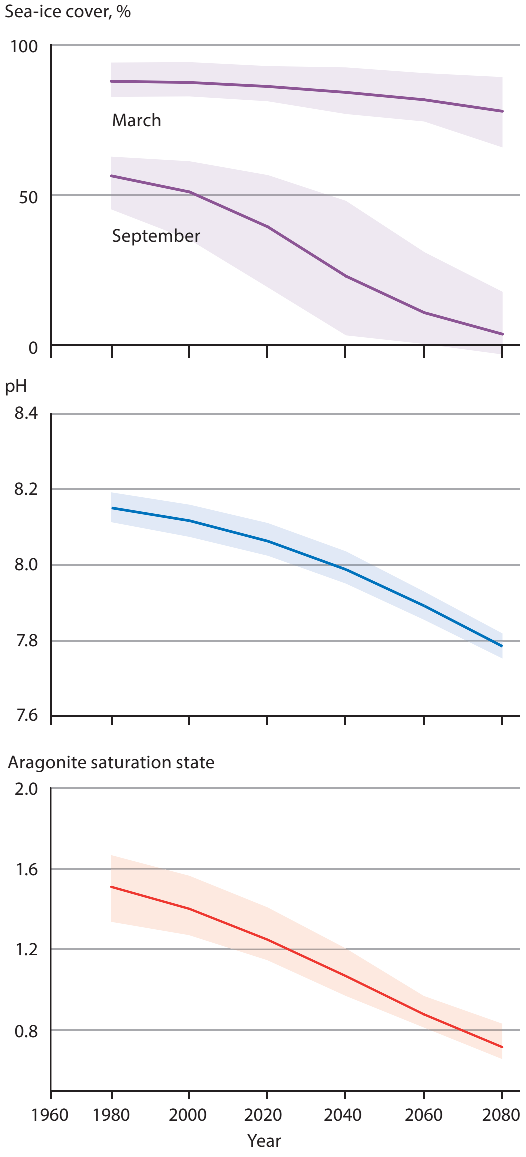
These general projections are widely accepted.

One significant uncertainty regards the release of methane gas from seafloor sediments. If continued warming speeds this release, the conversion of large amounts of methane to carbon dioxide could produce sharp increases in seawater acidity. Another uncertain aspect is whether future changes in primary production will hasten or slow acidification.

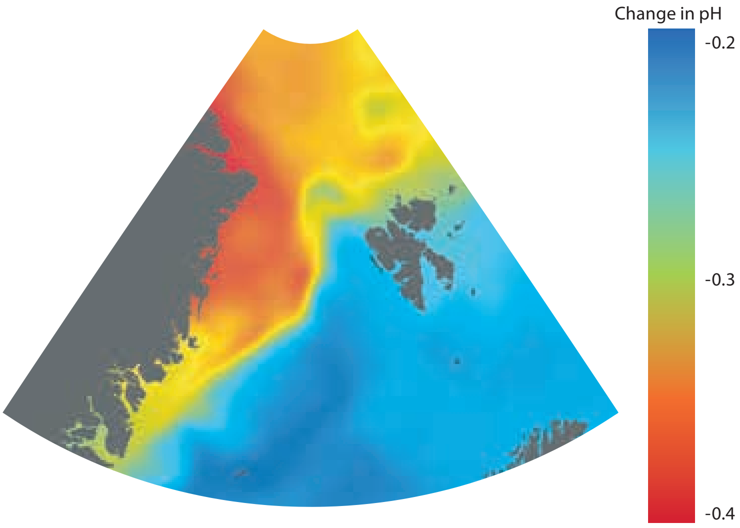
What does all this mean for **Arctic sea life?** The implications (pages 16 to 21) are uncertain at present, but so far the data suggest that:

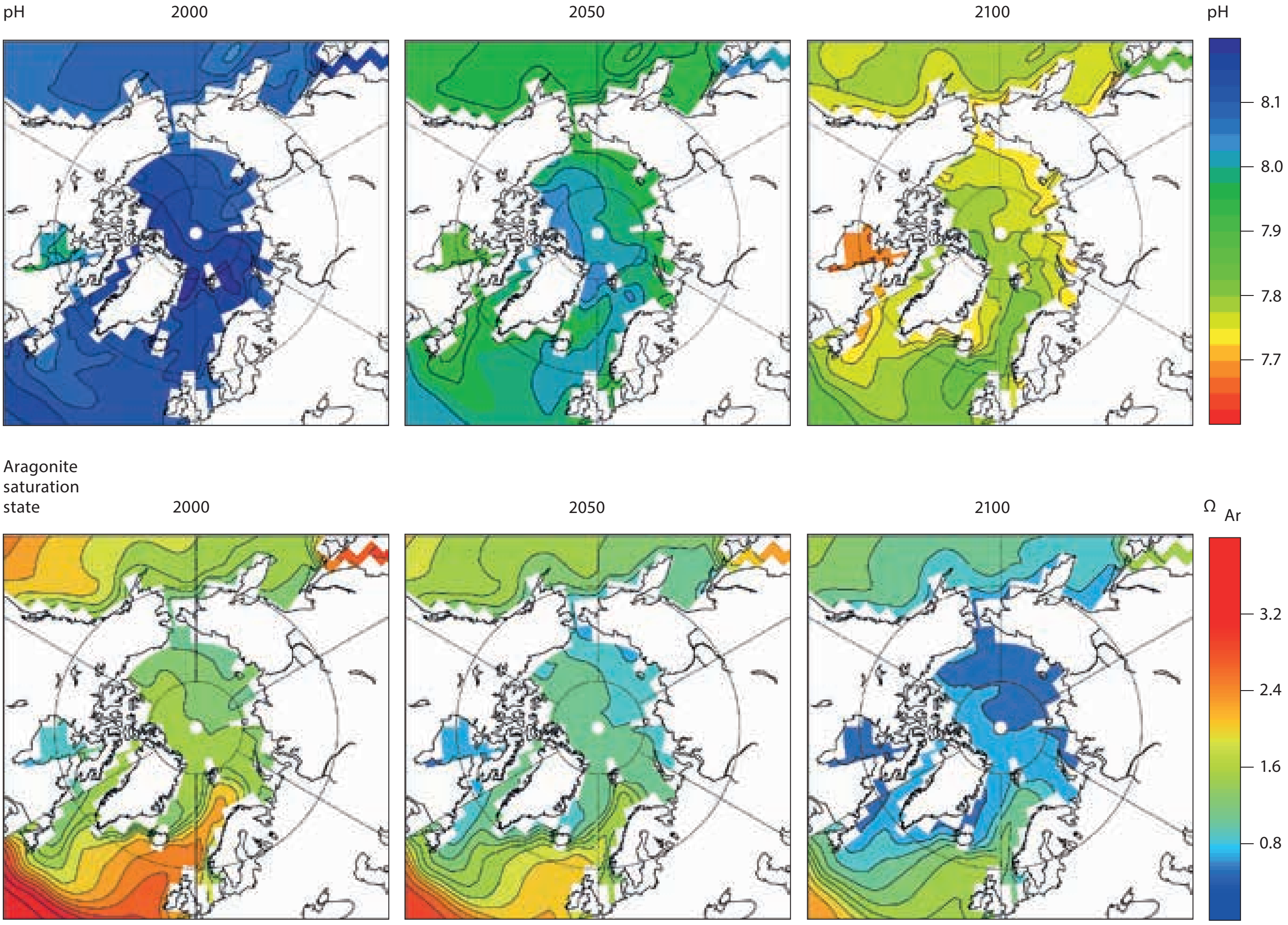
- Ocean acidification will affect Arctic marine life.
- It is likely that some Arctic marine organisms will respond positively to the new conditions while others will be disadvantaged, possibly to the point of local extinction.
- Arctic marine ecosystems are vulnerable to ocean acidification.

▶▶ Computer-model projections of future Arctic Ocean surface conditions.



▼ Modelled decrease in surface ocean pH over the 21st century in the Atlantic-Arctic gateway region.





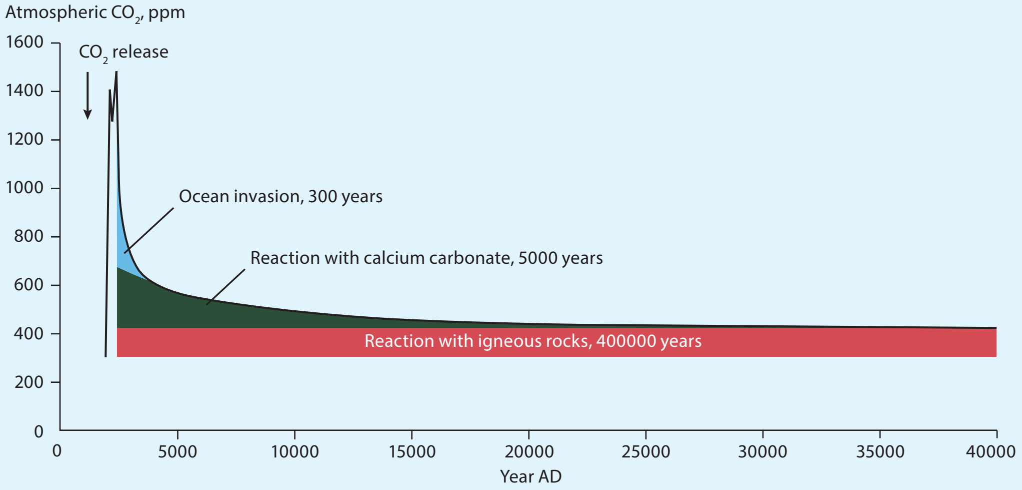
▲ Model projections of Arctic surface-ocean pH and aragonite saturation state through the 21st century.

LOOKING TO THE FAR FUTURE

The effects of today's ocean acidification will be **long-lasting.** As atmospheric carbon dioxide continues to climb, so will surface-ocean acidity. When atmospheric carbon dioxide stabilizes and declines, so will surface-ocean acidity.

Over time, the 'extra' acidity stored in the upper ocean will be mixed down into deeper waters. Eventually, some fraction of this acidity will be neutralized by the dissolving of calcium carbonate on the seafloor and then the weathering of igneous rocks. These neutralizing processes will take a very long time (thousands of years).

The fossil-fuel carbon released by human activities will remain in the ocean–atmosphere system for tens of thousands of years. Even then, ocean chemistry will not return to its pre-industrial state.



◀ Model simulation of atmospheric carbon dioxide after a large pulse of emissions from burning fossil fuels.

www.UWPhoto.no © Erling Svensen

CALCIFIERS OF THE ARCTIC

Many researchers have focused their studies on **calcifiers** – those plants and animals that make shells, skeletons, or other hard body parts of the mineral *calcium carbonate*. One reason is that ocean acidification may interfere with the biological process of manufacturing this mineral. Calcifiers of the Arctic include pteropods (shown here), corals, clams, oysters, and certain seaweeds.

David Littschwager

IMPLICATIONS FOR **ARCTIC MARINE LIFE**

OCEAN ACIDIFICATION WILL HAVE DIRECT AND INDIRECT EFFECTS ON ARCTIC MARINE LIFE

Data regarding the effects of ocean acidification on Arctic plants and animals are scarce. Assessments of potential Arctic impacts are therefore based largely on studies of non-Arctic plants and animals, interpreted with an understanding of Arctic organisms and ecosystems. Large uncertainties remain, but some inferences can be drawn.

DIRECT AND INDIRECT EFFECTS

Ocean acidification has the potential to affect a wide variety of sea life. Scientists are studying two general categories of impacts – *direct effects* and *indirect effects*.

Direct effects include changes in physiology or behavior. Examples include changes in sensory perception (for instance, sense of smell), growth rate, life-stage viability, immune system function, shell-building (for instance, calcification rate or shell strength), photosynthesis, respiration, metabolism, and reproductive success. Direct effects can be beneficial or detrimental.

Indirect effects are more difficult to observe and predict. Plants and animals that are not directly impacted may still feel the effects of ocean acidification via changes in their food supplies or other ecosystem connections – for example, changes in the pressures exerted by their predators or competitors.

Consider the case of walruses, which dine largely on mollusks and crustaceans. Because these prey items may be directly affected, walruses may in turn experience significant changes in the availability or quality of some of their preferred foods.

Another example: limited data indicate that some calcifying encrusting macroalgae (seaweed) may grow more slowly under future ocean acidification (a direct adverse effect). Their non-calcifying competitors may therefore benefit from the reduced competition for space and other limited resources (an indirect benefit).

Studies in other parts of the world are beginning to show that these indirect effects can be important. Indirect effects are perhaps the most likely way in which Arctic marine species will be affected.

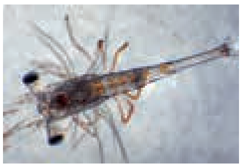
WINNERS AND LOSERS

Plants and animals exhibit a wide range of responses to ocean acidification. A few **general patterns** emerge from studies to date:

- **Calcifiers** – A wide range of calcifiers manufacture shells or skeletons more slowly when subjected to acidity levels projected for the coming centuries. Some calcifiers respond neutrally or even positively to high-carbon dioxide conditions.

Steve Gschmeissner/Science Photo Library

- **Early and transitional life stages** – Early life-history stages (especially larval forms) are generally more susceptible to acidification effects than later stages. Transitional life stages (molting, for example) are similarly times of heightened sensitivity.



International Research Institute of Stavanger

- **Attached organisms** – Plants and animals that live attached to the sea bottom are generally more susceptible to ocean-acidification effects than are floaters and swimmers. Some attached organisms are likely to be excluded from regions they previously occupied.

Fredrik Pleijel

- **Slow growers** – Arctic species generally grow slowly because they live immersed in frigid waters. Longer generation times may mean less capacity to adapt to rapidly changing conditions.

F. Welter Schultes, AnimalBase

- **Photosynthesizers** – Increased carbon dioxide may benefit some plants and algae that use carbon dioxide for photosynthesis. Seagrasses, non-calcifying seaweeds, and some phytoplankton species are among those likely to benefit directly. Some non-calcifying organisms may benefit indirectly if their calcifying competitors suffer adverse impacts.

Michel Braunstein

© Josef Wiktor / Norwegian Polar Institute

Sam Dupont

Fredrik Pleijel

Sam Dupont

ROLL CALL: A SURVEY OF ARCTIC MARINE LIFE

Viruses are abundant in seawater and especially sea ice. Viral responses to elevated carbon dioxide are poorly studied, and results are highly variable. No studies definitively show direct ocean-acidification effects on marine viruses. Because the life cycles of viruses are tied to the lives of their hosts, viral processes may be indirectly influenced by acidification.

Bacteria are important in not only seawater but also sea ice. The current consensus is that marine bacterial communities will not be directly affected by the acidity increase projected for the end of this century. In some studies, bacterial communities respond indirectly to acidification through their interactions with directly affected phytoplankton. Ocean acidification might affect some food webs in which microbes participate.

Phytoplankton are the dominant photosynthesizers in Arctic marine ecosystems. They show no consistent across-the-board response to ocean acidification. Most calcifying forms show decreased calcification, but some recent studies conclude that a number of marine phytoplankton are resilient to acidification impacts.

Foraminifera include both calcifying and non-calcifying species. Limited evidence indicates that mild ocean acidification will have few if any effects on foraminiferal survival but may influence growth rates. Increasing carbon dioxide generally results in less massive shells. More extreme levels of acidification are likely to reduce the survival and diversity of the calcifiers. The ecosystem consequences of increased dominance by non-calcifying species are unknown.

Macroalgae (‘seaweeds’) come in both calcifying and non-calcifying forms. Calcified macroalgae may be particularly vulnerable to future ocean acidification because many polar species are only weakly calcified and their growth may be compromised. Most non-calcifiers will probably benefit directly (more carbon dioxide for photosynthesis) and indirectly (decreased competition from calcifiers).

Corals build aragonite reefs and gardens that provide important habitat for many organisms, including commercially important fishes. Ocean acidification may have limited impacts on the most well-known cold-water coral (*Lophelia*), especially if well fed. Effects on early life stages and other cold-water species are unknown. Older *Lophelia* skeletons and dead reef mounds are likely to dissolve in aragonite-corrosive waters. The ecological consequences of this potential loss of sea-bottom habitat are not known.

Mollusks are a highly diverse collection of animals, encompassing bivalves (including oysters and mussels), gastropods (snails), and cephalopods (including squids and cuttlefishes). A wide range of biological responses to ocean acidification has been exhibited by this group, which includes many calcifying species. Bivalves, pteropods (‘sea butterflies’; a subgroup of gastropods), and cephalopods are important components of Arctic food webs. Impacts to these species could have ripple effects for Arctic ecosystems. Calcifying mollusks are likely to be negatively impacted by ocean acidification – especially thin-shelled floaters, such as some pteropods, and sensitive early life-history phases. Effects on ecologically important non-calcifying or poorly calcifying species (squids, for example) are unknown.

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Peter Prokosch

Echinoderms include sea urchins, starfish, and brittle stars. This group is relatively well studied because it includes ecologically important calcifiers. Most echinoderms calcify as larvae and as adults; some use a relatively unstable form of calcium carbonate. Some studies of polar echinoderms report neutral responses to ocean acidification, but the majority of responses have been negative. Changes in echinoderm abundance would likely have broader impacts for Arctic seabed ecosystems.

Crustaceans include copepods, crabs, lobsters, and barnacles. Many are highly calcified, and many play key roles in Arctic ecosystems. Copepods, for example, are the predominant plant-eaters and also a key food source for larger animals, including polar cod. Crustaceans overall seem to be generally relatively robust to ocean acidification, but tested polar and Arctic species have shown significant reductions in function, especially during larval stages. Such impairments are likely to mean lower survival rates. No study has reported acidification impacts to copepods under carbon dioxide levels projected for the next two centuries.

Other invertebrates have been seldom studied. Outside the groups mentioned above, only one polar species, an Antarctic ribbon worm, has been reported on. For that animal, anticipated near-future acidification conditions had no significant effect on the life phases examined.

Fishes are of tremendous importance to the ecosystems, economies, and cultures of the Arctic. The effect of ocean acidification on Arctic fishes is unknown. Studies of Atlantic cod and walleye pollock from more southerly populations indicate a generally robust response, but populations adapted to Arctic conditions may be more sensitive. Larval fish are predicted to be more sensitive than adults, but until multi-generational studies are conducted, such conclusions would be premature. In terms of indirect effects, polar cod have been a particular concern because they serve as a pillar of Arctic marine ecosystems and they rely heavily at all life stages on copepods. However, copepod studies indicate that acidification is unlikely to diminish the availability of this favored prey.

Seabirds and marine mammals feed on the ice, in the water, and on the sea bottom. Ocean acidification is not likely to affect these animals directly. The effects they might experience would be indirect, through food-web linkages. Seabirds and mammals that feed on calcifying species such as bivalves or pteropods, for example, may need to switch to other food sources if these prey animals disappear or decline due to acidification.

Fisheries species are discussed further on pages 22 to 24.

NEW DIRECTIONS: COPING WITH OCEAN ACIDIFICATION

Researchers are just beginning to explore these important aspects of biological responses to ocean acidification:

- **Acclimatization** – How well can individual plants or animals adjust to life in a higher-acidity ocean?
- **Adaptation** – How nimbly can a species evolve over the generations to produce offspring that survive and thrive in higher-acidity waters?
- **Simultaneous environmental changes** – How well do different organisms cope with real-world combinations of environmental changes – for example, not only elevated acidity but also higher temperatures, less-salty waters, and shifting food webs?

IMPLICATIONS FOR
ARCTIC MARINE ECOSYSTEMS

OCEAN ACIDIFICATION IMPACTS MUST BE ASSESSED IN THE CONTEXT OF OTHER CHANGES HAPPENING IN ARCTIC WATERS

Arctic marine ecosystems are vulnerable to ocean acidification, but precise implications are unknown. Studies to date have highlighted the possibility of Arctic vulnerability and the certainty of ecosystem complexity.

Arctic food webs are relatively simple and are therefore susceptible to disruption. As noted on page 4, Arctic marine ecosystems are characterized by a small number of key species at each trophic level. Phytoplankton constitute the dominant photosynthesizers, at the base of the food web. Large copepods are the predominant plant-eaters. Pteropods, krill, and small fishes also serve to link lower trophic levels to higher ones, which are populated largely by seabirds and marine mammals. Humans are the apex predators.

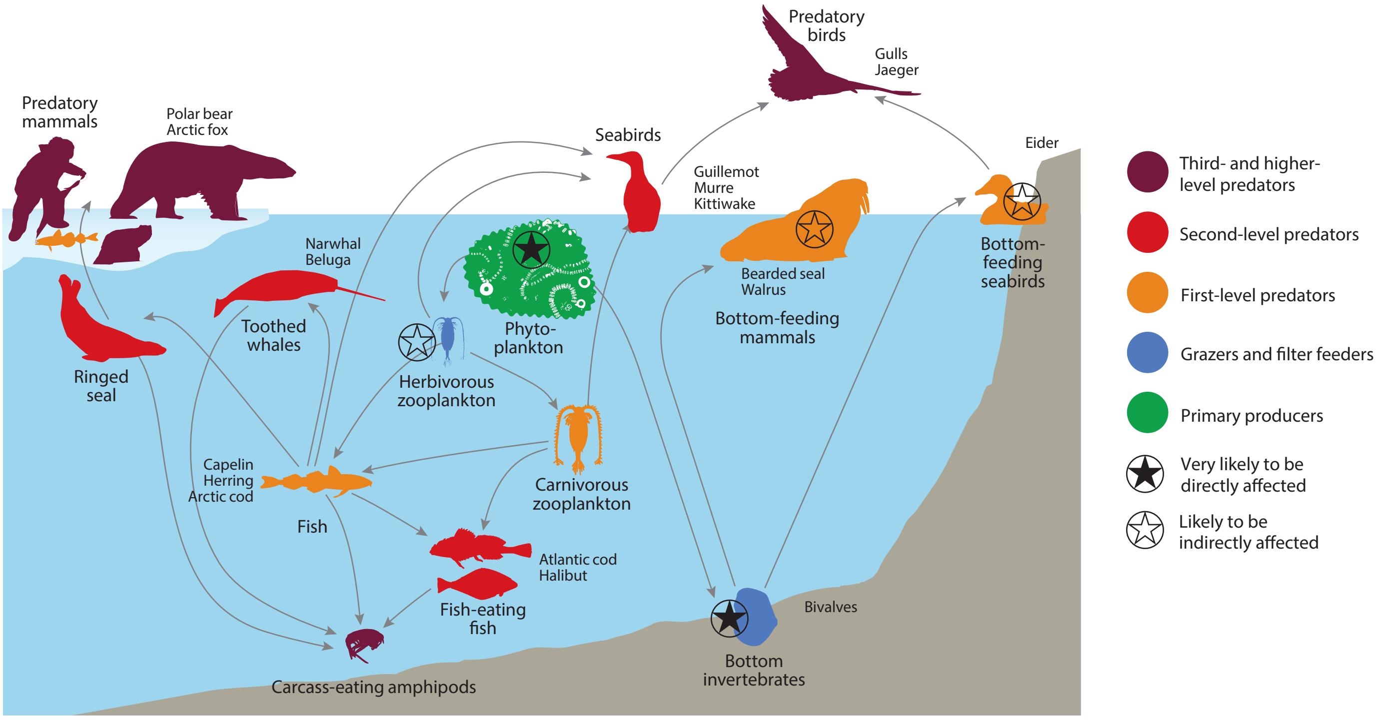
This relatively simple structure limits the options for food webs to accommodate environmental change. If a key food species goes extinct or leaves the area, few alternatives are available unless new food species move in. Predators and other consumers may need to switch to new food sources or relocate.

Arctic Ocean acidification is occurring simultaneously with other large-scale, rapid environmental changes. Scientists have not yet assessed the combined effects of Arctic Ocean warming, freshening, and acidification. All of these changes are happening now.

The major driver of change is Arctic warming. In the past few decades, summer temperatures have been higher than at any other time in the past two thousand years. The summertime ocean will probably be nearly ice-free within 30 to 40 years.

For the ocean, this extent of warming means a cascade of change. Sea-ice retreat, for example, does not just mean a loss of sea-ice habitat. The retreating ice edge also exposes more of the ocean surface to the carbon dioxide–rich atmosphere. Melting ice caps and glaciers add fresh water to the sea. Thawing permafrost liberates long-stored carbon. All of these changes tend to accelerate ocean acidification or intensify its impacts.

Other changes are happening too. Some global pollutants, such as mercury, accumulate in the far north. Humans heavily harvest local animals, some to the point of population collapse. New species and industries are moving in. Arctic plants and animals must cope with all of these changes simultaneously.



So far, though, most research studies have looked only at how single species respond to acidification alone. These studies are an essential starting point, but they do not tell the whole story.

Ecosystem effects are far more complex. Multiple stresses exerted at the same time may act together to heighten environmental impacts. Or one stressor may counteract the impacts of another. Sometimes stressor effects do not interact at all.

Marine organisms are experiencing changes in not only their physical environment but also their encounters with each other. For example, two species of coldwater fish may leave a warming ocean area, but one may move farther, encountering new predators or new foods. Two species of shellfish may grow more rapidly under higher temperatures, but one may ramp up faster and gain a competitive edge. Two competing echinoderms may respond oppositely to acidification, with one thriving and one failing. The result of all these differences is an ever-adjusting web of complex interactions among all manner of neighbors, from predators to parasites.

The interplay of complex plant and animal responses to changing environmental conditions and to each other can produce unexpected, non-intuitive outcomes. Consider the case of shore crabs that feed on periwinkles. Ocean acidification weakens the crabs’ claws, thus making them less effective predators. However, ocean acidification also weakens the snails’ protective shells. Who wins? In this study, no one. Experimental ocean acidification produced no overall change in the crabs’ consumption of the periwinkles.

Few studies have investigated the combined effects of biological and non-biological factors on responses to ocean acidification. No such data are available for Arctic food webs.

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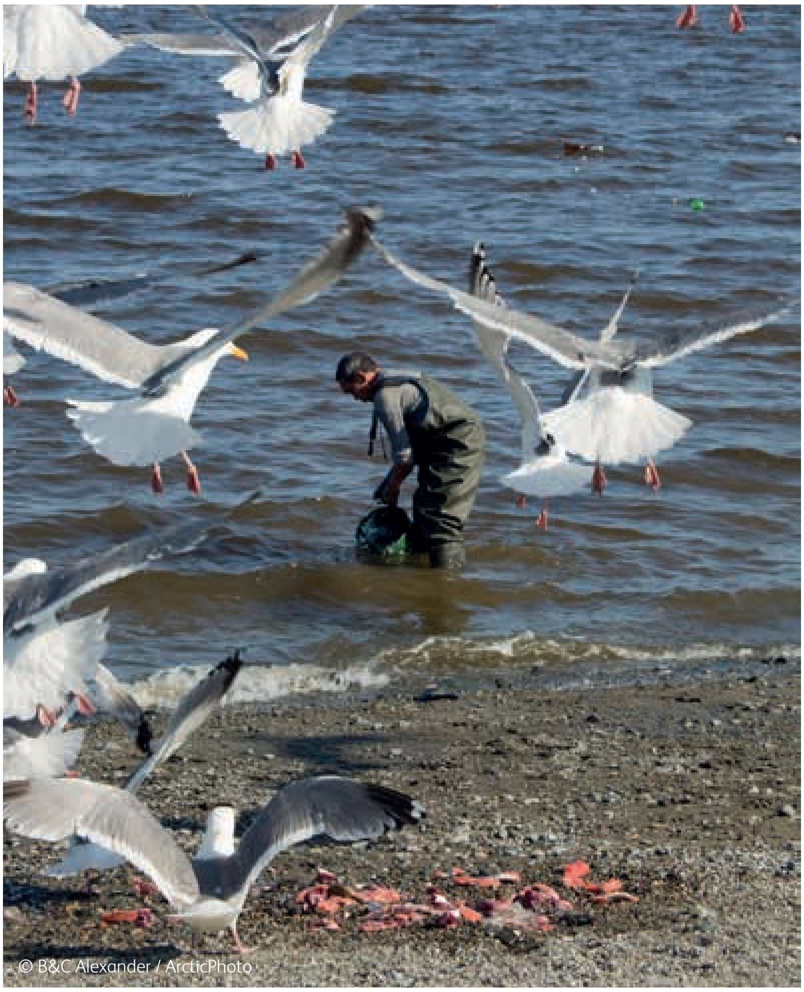

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IMPLICATIONS FOR ARCTIC MARINE FISHERIES

OCEAN ACIDIFICATION MAY AFFECT MARINE FISHERIES AND THE LIVELIHOODS OF ARCTIC PEOPLES

Arctic waters provide not only valuable finfish and shellfish for a variety of fishers but also recreational experiences for residents and tourists. In 2002, fisheries of the circumpolar north accounted for more than 10% of the world's wild-fish catch and more than 5% of the crustacean catch. Most recreational fishing is still local, but tourism, including ecotourism, is one of the fastest-growing Arctic industries. Indigenous peoples still rely largely on locally harvested food.

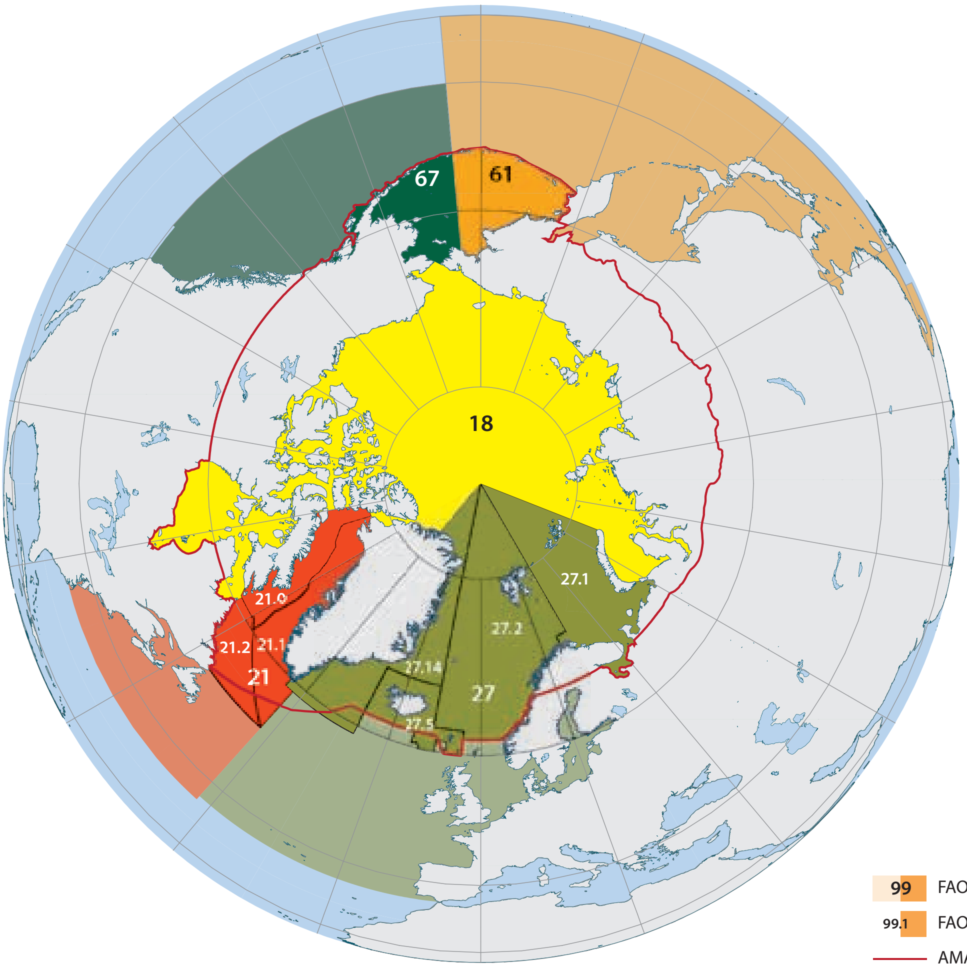
Ocean acidification is likely to affect Arctic fisheries by changing the abundance, productivity, and distribution of Arctic marine species and therefore fishing costs, fish prices, and fisheries benefits. The magnitude and direction of the changes are uncertain. Rising temperatures and diminishing sea ice will also be important, probably dominating, factors.

More certain statements are not yet possible because of the dearth of economic studies of ocean-acidification impacts, especially for the Arctic. Additional data are needed.


Corey Arnold


Bryan and Cherry Alexander


Christophe Boisvieux / Corbis

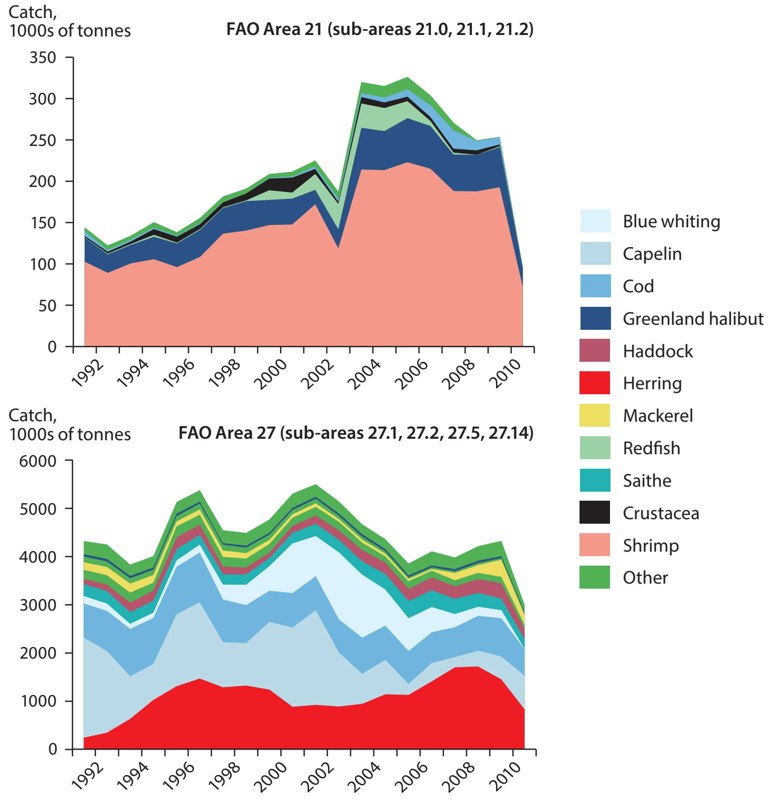


◀ Fishing areas in Arctic waters (numbers denote FAO fishing-area designations).

REGIONAL CONSIDERATIONS

Based on the current understanding of Arctic Ocean acidification (pages 1 to 15) and biological responses (pages 16 to 21) plus knowledge of today's **regional Arctic fisheries**:

- If ocean acidification is stronger in surface waters than in deep waters, then **shelf species** may be affected more than deepwater species.
- If ocean acidification impacts are more severe in areas of melting sea ice, then **Low-Arctic regions** may be affected more than sub-Arctic regions.
- If food webs are less complex in Low-Arctic regions than in sub-Arctic regions, then negative effects on catch composition and total output may be greater for **Low-Arctic fisheries.**
- If mollusks are more susceptible to ocean acidification impacts than other fisheries species, then **northwestern Atlantic fisheries** (which rely more heavily on bivalves and gastropods) may suffer more than northeastern Atlantic fisheries.
- If ocean acidification affects mainly crustaceans and mollusks at lower trophic levels, then **recreational fishing** may be hardly affected, unless some indirect impact is propagated via food webs.



▲ Catches of main species in the Arctic parts of FAO Fishing Areas 21 and 27.

Yukon Council of First Nations

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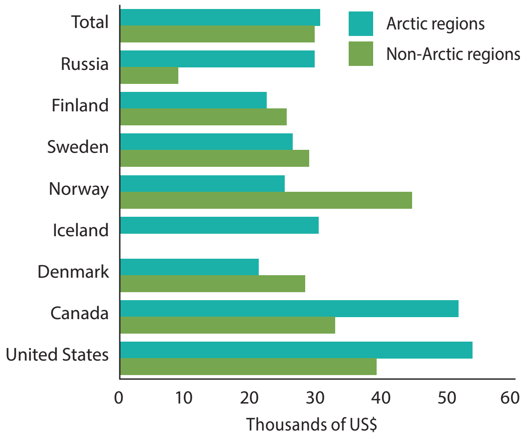
Gross regional product (at purchasing power parity) per capita in 2005



INDIGENOUS PEOPLES AND LOCAL COMMUNITIES

Ocean acidification poses a potential risk to Arctic food systems, cultures, and livelihoods. Some traditional food species may be susceptible to direct effects. Others may be immune to direct effects but subject to food-web ripple effects. (For an explanation of direct and indirect effects, see page 17.) Evidence suggests the following:

Harvested species **extremely likely** to be **directly** affected by ocean acidification: clams and scallops.

Harvested species **very likely** to be **directly** affected by ocean acidification: crab, shrimp, and Norway lobster/langoustine.

A harvested species at **high risk** of **indirect** (prey-related) effects is the Atlantic wolffish (ocean catfish) because its diet includes animals deemed to be extremely or highly likely to experience acidification impacts.

These harvested species, which feed on a mixture of directly impacted and non-impacted prey, are at **medium risk** from **indirect** (prey-related) effects:

- Fish: rough dab; redfish; Arctic char; haddock; Atlantic cod, Greenland halibut, mackerel; salmon; blue whiting, herring; blue ling; muksun, Siberian sturgeon, tusk; capelin.
- Crab.
- Marine mammals: bearded, harbor, and hooded seals; walrus; narwhal; harp and ringed seals; bowhead whales; fur seals, pilot whales, sea lions.
- Seabirds: Arctic tern, ducks, sea gulls, eider, dovekie, thick-billed murre, black guillemot.

KNOWLEDGE GAPS & MANAGEMENT MEASURES: NEXT STEPS

Programs to monitor Arctic Ocean acidification and study its impacts must be designed for the unique environmental conditions and cultures of the far north. Responding effectively to the changing conditions will require attention to overall resilience and sustainability.

ARCTIC MONITORING

The Arctic is one of the Earth's **most rapidly changing** regions, yet it is also one of the most **poorly sampled** and **least understood**. Long-term observations are needed.

- Monitoring of the seawater carbon dioxide system should be:
  - Integrated within a framework that also monitors changes in other key variables (such as oxygen and nutrients).
  - Closely coordinated with physical and biological observations.
  - Conducted from ships and *in situ* platforms (stationary and mobile).
- New instrumentation will need to be developed for the extreme Arctic conditions.
- Management of platform design, observational logistics, and data handling should be internationally coordinated.

EXPERIMENTAL DIRECTIONS

Almost no information is available regarding ocean-acidification effects on Arctic **keystone species and processes**. Focused research is urgently needed. General high-priority needs include:

- Investigation of direct and indirect effects on Arctic and sub-Arctic organisms, including key food-web species and commercially important species.
- Experiments conducted *in situ* (that is, in the ocean rather than in laboratories) and at ecologically relevant timescales.
- Assessments of Arctic organisms' capacity for acclimatization at all life stages and for adaptation over several generations.
- Investigation of the effects of multiple and simultaneous environmental changes on species- and ecosystem-level processes.

AN INTERDISCIPLINARY APPROACH IS ESSENTIAL

SOCIO-ECONOMIC CONSIDERATIONS

Economists and other social scientists use theoretical and simulation modeling together with scenario-building to study the societal impacts of ocean acidification. Achieving more comprehensive assessments with a greater degree of certainty will require **additional data** from the marine and life sciences.

In light of the current understanding of ocean acidification and Arctic culture and marine resources, the following **management measures** are recommended:

- Marine protected areas, carefully designed to increase habitat resilience and support fish and shellfish populations for sustainable harvests.
- Strategies for sustainable development and tourism.
- Strong ecosystem-based management initiatives.

Additional considerations:

- Fish stocks will be more resilient to ocean acidification if other stresses are minimized (for example, overfishing and habitat degradation).
- Adaptive aquaculture management (for instance, selection of acidification-resistant species) may enhance economic and social opportunities.
- Incorporating traditional knowledge within a long-term participatory approach to fisheries management would be beneficial.

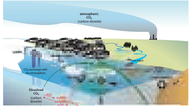
Because ocean acidification is occurring simultaneously with other large-scale and rapid environmental changes, **marine ecosystems must be managed for overall resilience.**

MARINE ECOSYSTEMS MUST BE MANAGED FOR OVERALL RESILIENCE

FIRST AMAP ARCTIC OCEAN ACIDIFICATION ASSESSMENT: 10 FINDINGS

Acidification in the Arctic Ocean

1. Arctic marine waters are experiencing widespread and rapid ocean acidification. Recent chemical measurements at several Arctic Ocean locations indicate significant rates of acidification. The combination of ocean acidification and melting ice is driving other widespread changes in the chemical make-up of Arctic seawater, especially in the upper ocean.

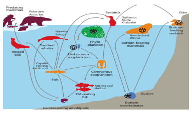


2. The primary driver of ocean acidification is uptake of carbon dioxide emitted to the atmosphere by human activities. The burning of carbon-rich materials such as coal or oil releases carbon dioxide to the atmosphere. The oceans absorb some of this gas, and the result is an increase in the acidity of the seawater. The average acidity of ocean-surface waters worldwide is now about 30 %[14] higher than at the start of the Industrial Revolution.

3. The Arctic Ocean is especially vulnerable to ocean acidification. The Arctic Ocean is cold, and its sea-ice cover is retreating. Both of these factors favor the transfer of carbon dioxide from the air into the ocean. In addition, the Arctic Ocean receives large quantities of fresh water from rivers and melting ice. As a result, Arctic seawater is less effective at chemically neutralizing carbon dioxide's acidifying effects.

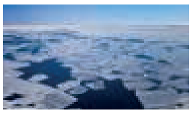
4. Acidification is not uniform across the Arctic Ocean. While seawater uptake of carbon dioxide is the primary driver, other processes can also influence the local pace and extent of ocean acidification. Rivers, sea ice, coastal and sea-bottom sediments, and biological production and decay can all play a role. The contributions of these processes vary from place to place, season to season, and year to year.

Biological responses to ocean acidification



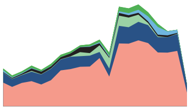
5. Arctic marine ecosystems are highly likely to undergo significant change due to ocean acidification. Arctic marine ecosystems are generally characterized by short, simple food webs that depend greatly on certain key species. Some of these key species may be sensitive to ocean acidification. Too few data are available to assess precisely the nature and extent of Arctic vulnerability. Arctic-specific long-term studies are urgently needed.

6. Ocean acidification will have direct and indirect effects on Arctic marine life. It is likely that some marine organisms will respond positively to new conditions associated with ocean acidification, while others will be disadvantaged, possibly to the point of local extinction. Examples of direct effects include changes in growth rate, shell formation, or animal behavior. Examples of indirect effects include changes in food supply, predation, or livable habitat.



7. Ocean acidification impacts must be assessed in the context of other changes happening in Arctic waters. Arctic marine organisms are experiencing not only ocean acidification but also other large, simultaneous changes – for example, changes in climate, fisheries harvesting, and suitable habitat. As different forms of sea life respond in different ways, the mix of plants and animals will change, as will their interactions with each other.

Potential economic and social impacts of ocean acidification on Arctic fisheries



8. Ocean acidification is one of several factors that may contribute to alteration of fish species composition in the Arctic Ocean. Ocean acidification is likely to affect the abundance, productivity, and distribution of marine species, but the magnitude and direction of change are uncertain. Other processes driving Arctic change include rising temperatures, diminishing sea ice, and decreasing saltiness of surface waters.

9. Ocean acidification may affect Arctic fisheries. Few studies have estimated the socio-economic impacts of ocean acidification on fisheries, especially Arctic fisheries. Commercially important Arctic fish stocks may be affected by ocean acidification, but the magnitude and direction of change are uncertain. Fish stocks may be more robust to ocean acidification if other stresses such as overfishing and habitat degradation are minimized.

10. Ecosystem changes associated with ocean acidification may affect the livelihoods of Arctic peoples. The marine harvests of northern coastal communities include species likely to be affected by ocean acidification. Most indigenous groups harvest a range of organisms and may be able to accommodate adverse impacts by shifting to a greater reliance on unaffected or favorably impacted species. Changing harvests might affect some seasonal or cultural practices, and recreational fish catches could change in composition. Marine mammals could be indirectly affected through changing food supplies.

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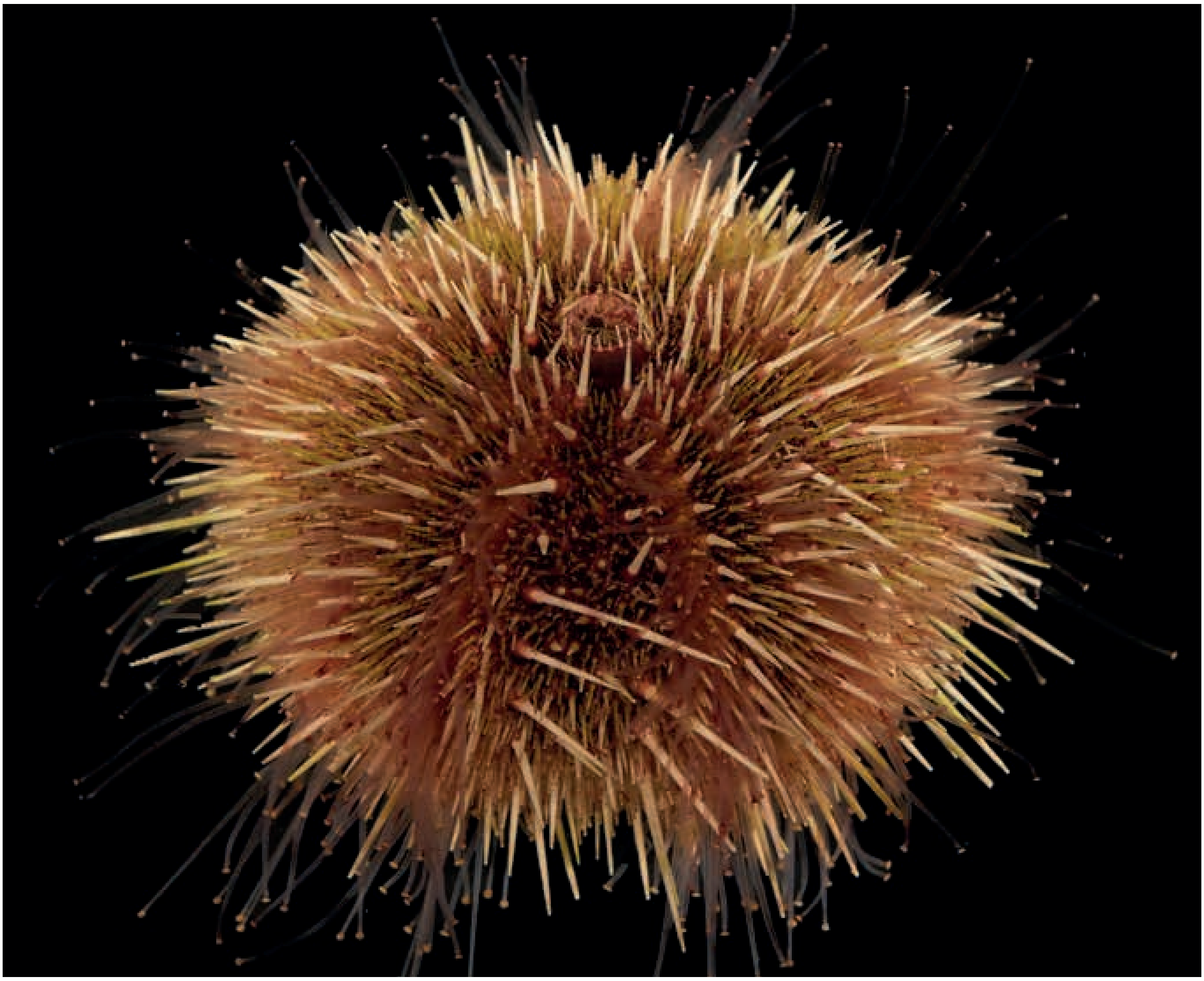
[14] According to the IPCC Working Group I report, the pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26 % increase in hydrogen ion concentration.



Information on Arctic species and ecosystem processes is extremely limited (see page 17 and page 25). This is illustrated by the example of sea urchins. The numbers on the map indicate numbers of published studies. Source: Sam Dupont, University of Gothenburg.

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