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FACT SHEET

THE CONSEQUENCES OF CLIMATE CHANGE FOR LIFE IN THE Arctic Ocean

Getting warmer faster than anywhere else

There is scarcely a region on Earth that has become warmer since the mid-20th century so quickly as the Arctic. The air temperature there has risen twice as fast as on the global average. The consequences of this warming process appear most clearly in the constantly declining sea ice cover. Scientists presume that the North Pole could be ice-free in summer in less than 40 years.

The melting sea ice opens up new opportunities for some dwellers of the Arctic Ocean, but for many others the foundation of their life is disappearing. That means climate change already poses great challenges for a tried and tested system of highly specialised plants and animals. As the water temperature rises, for instance, more species migrate from the south to the north and compete for space with the dwellers there. But where should the native local species go? For many of them there are practically no alternative places of refuge in even colder regions.

Furthermore, more freshwater enters the Arctic Ocean via large rivers and melting sea ice today than previously. This low-saline water acts like a lid over deeper water layers and prevents nutrients from reaching the surface. At the same time more and more carbon dioxide dissolves in the surface water of the ocean due to the high greenhouse gas concentration in the atmosphere. As a result, the pH value of the water drops. Living organisms that form their shell and skeleton out of calcium can produce less building material.

The home of the polar bear is the Arctic, whose southern boundary is drawn at 66 degrees latitude North by the World Climate Council. This fact sheet is oriented to this definition. (Photo: Sebastian Menze/AWI)

Scientists at the Alfred Wegener Institute have been investigating how the ecosystem of the Arctic Ocean is changing for several decades. This fact sheet provides an insight into their research and results.

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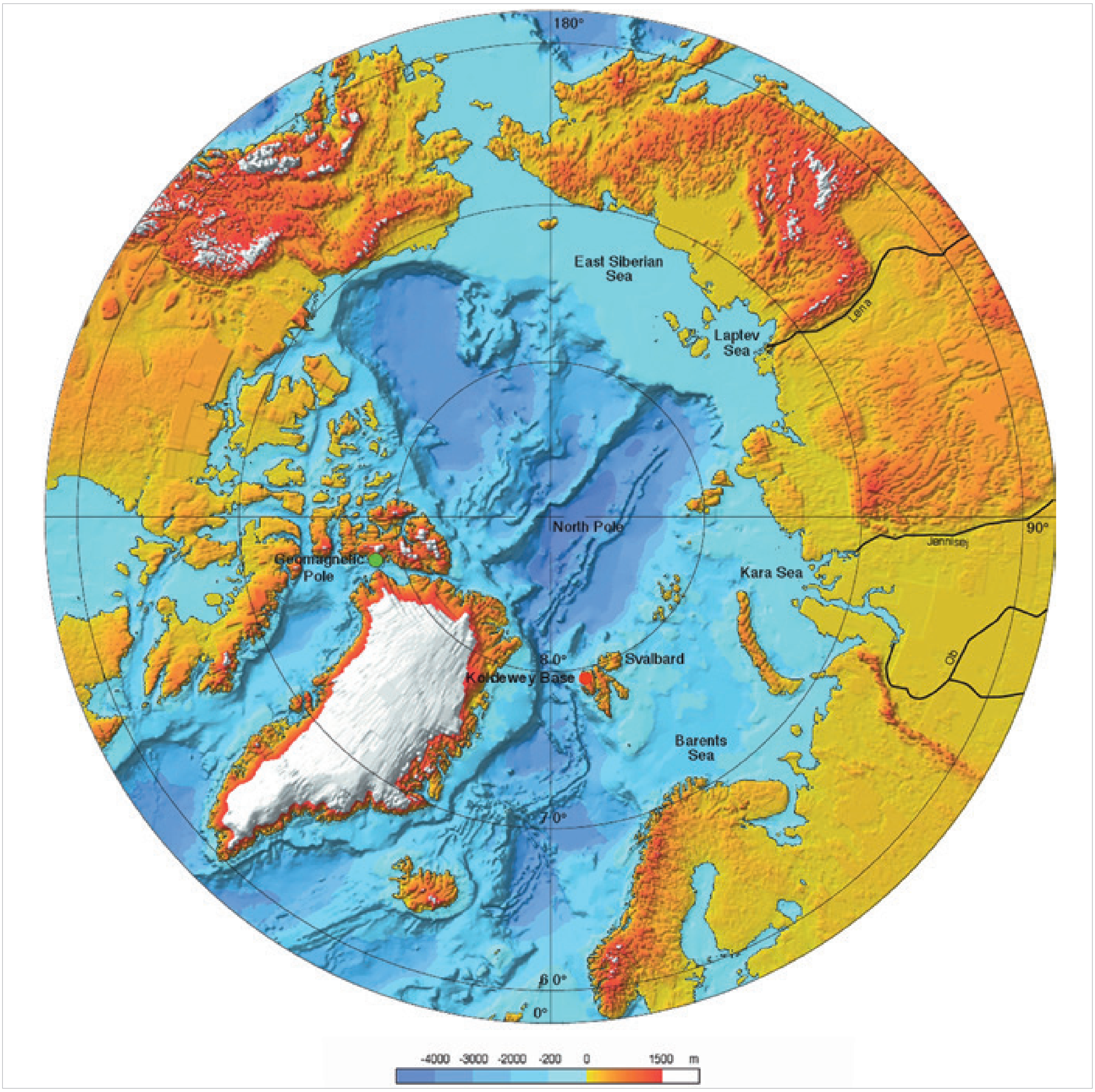


The Arctic Ocean

The Arctic is, in contrast to the Antarctic, not a continent. Rather, it stretches across a central ocean that is surrounded by the northern edges of Scandinavia, North America, Greenland and Russia. With a length of 4,000 kilometres, a width of 2,400 kilometres and an area of 14 million square kilometres the Arctic Ocean is the smallest ocean on our planet. It lies completely within the northern polar circle, its territory includes large shallow shelf seas, such as the Laptev Sea, and it possesses water masses directly under the ice with a minimum temperature of minus 1.8 degrees Celsius.

Life in the ocean is significantly influenced by the circulation of the water and thus by the topography of the seafloor. The map shows four deep-sea basins separated from one another by underwater mountain ranges. The only deep-sea connection between the Arctic Ocean and other oceans runs through the Fram Strait – the passage between Greenland and Spitsbergen.

Climate change impacts walruses in two ways. Not only is their most important hunting and resting platform, i.e. sea ice, melting away. Mussels, their main food, are presumably hard hit by acidification of the ocean. (Photo: Magnus Elander, CC BY-NC-ND 4.0)

The consequences of climate change for the Arctic Ocean

Warming, acidification, altered stratification of water masses – three consequences of climate change that hit the dwellers of Arctic waters hard, especially when they occur simultaneously. As a trio, they mutually reinforce their impact so that even fish hardly affected by acidified water alone react sensitively to ocean acidification if the water temperature rises at the same time. Here are some selected general facts and forecasts regarding the consequences of climate change in the Arctic Ocean.

Warming

The temperature of the Arctic Ocean at a medium water depth has risen by up to 0.9 degrees Celsius per decade since the 1970s. The consequences include:

- Species from more southerly areas settle in Arctic waters and compete for food with native species there. The species composition changes. For people this means food fish migrate to the north and fishing areas shift.

- Due to the decline of sea ice, the primary production of ice algae will decrease. Their growth and reproduction make up nearly half of the food base in the ecosystem of the Arctic Ocean.

Stratification

If freshwater enters the Arctic Ocean via rivers, precipitation or melting sea ice, it alters the ocean's surface water. The salt concentration of the upper water layer and thus its density decrease. The consequences:

- If the upper water layer has a significantly lower density than the water masses below it, mixing of the two layers may increasingly deteriorate. That means the more pronounced the stratification, the less frequently nutrients from the lower water layers reach the upper layers.

- Increasing stratification influences the oceanic currents and the convection of the water with which the deeper layers of the ocean are supplied with oxygen.

Acidification

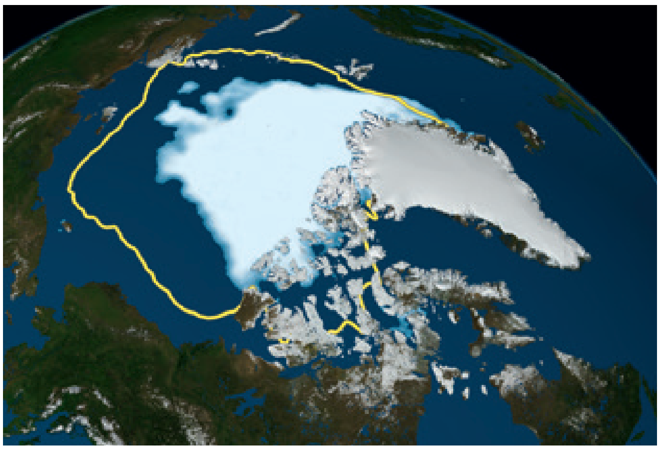
Carbon dioxide dissolves extremely well in cold seawater, especially when it mixes with freshwater. Buffering salts are diluted in this way. Arctic waters therefore number among the regions that will be hardest hit by ocean acidification. Carbon dioxide additionally disrupts the formation of carbonate in the body fluids of marine dwellers. This means species that build their shells out of calcium or aragonite no longer have adequate building material.

One of the many melt ponds that form on the sea ice of the Arctic in summer shimmers turquoise-blue. The thinner the ice layer at the bottom of the pond, the darker its colour because the ocean shimmers through the ice from below. At such ponds AWI biologists investigate, among other things, the conditions under which ice algae grow in pools of melt water. (Photo: Stefan Hendricks, AWI)

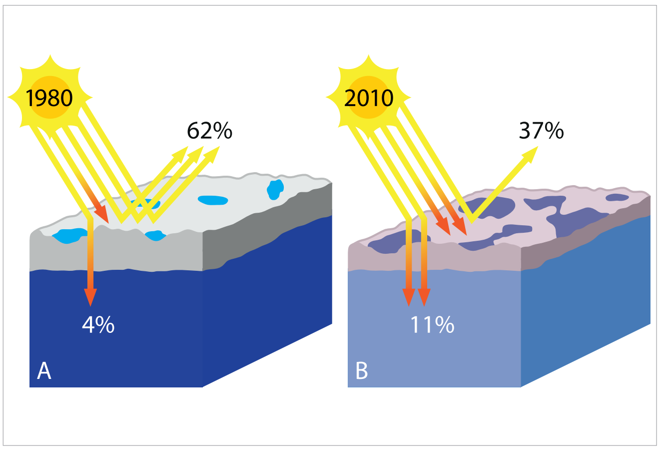
Less ice, more delicacies for the deep sea

Nowhere else are the consequences of climate change so clear and obvious as in the Arctic sea ice cover. It has not only become smaller in the past 25 years, but also a lot thinner. Where ice up to four metres thick and four years old or more used to drift in summer, researchers now usually find a carpet of approx. 90-centimetre thin, one-year-old floes on their expeditions. This ice is covered with melt ponds and can hardly perform its most important climate function – reflection of sunlight. Instead, it absorbs more than half the sun's rays. A growing portion of the light even penetrates through the ice and presumably gives biocoenoses living in and under the ice additional energy for large-scale growth. Highly specialised Arctic dwellers like ice algae require only a little light to reproduce. Ice algae is the designation for different algae species that live in the brine channels of the ice or on the bottom of floes. They produce nearly half the food base in the Arctic Ocean. If they multiply, the polar cod and fellow species have more to eat.

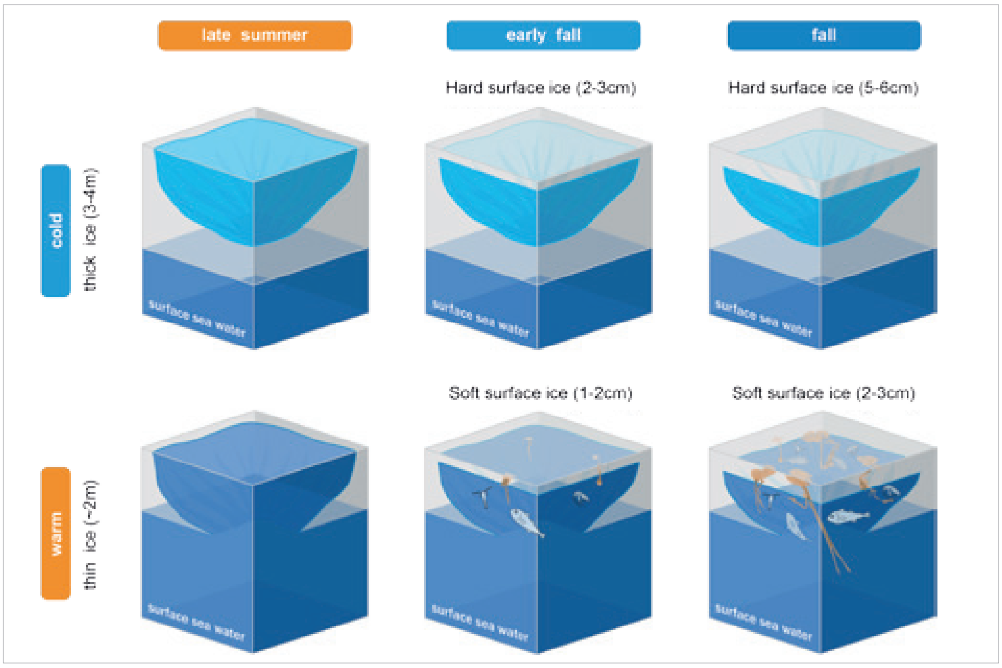
The ice alga *Melosira arctica* has proven to be an extremely good light harvester. On a Polarstern



In summer 2012 the Arctic ice cover shrank to a record September minimum of 3.41 million square kilometres (white area). This figure was far below the average area of the years 1979 to 2010, which is shown here as a yellow line. (Map: NASA/Goddard Space Flight Center Scientific Visualization Studio)



In 1980 the pack ice in the Arctic was so thick that it reflected more than 60 percent of the incident solar energy. This figure has nearly dropped by half since then. The remaining ice is often only one winter old, thin, covered by many melt ponds, and therefore unable to reflect much light. (Graphics: AWI)



Larders in the ice

Melt ponds are not a new phenomenon in the Arctic. They existed in the past, with the difference that the air was colder and the pack ice thick enough not to melt through. The thin ice of today can offer but little resistance to the warming process. When shallow ponds form in the summer, they quickly develop into bottomless holes. When they freeze over in late summer, however, more ice algae grow in the cavities than under the floe. New larders that provide food for copepods and polar cod come into being, particularly at the beginning of the long winter.

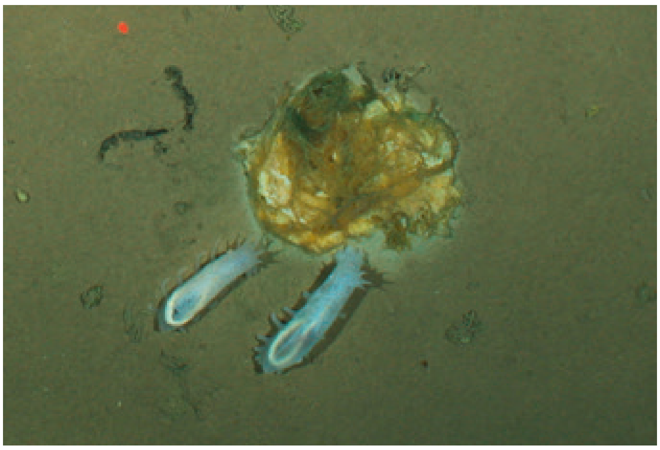
(Figure: Lee, S.H et al. 2011. Holes in progressively thinning Arctic sea ice lead to new ice algae habitat. Oceanography 24(3): 302-308)

expedition to the central Arctic in summer 2012 AWI researchers found this organism in large carpets under the thin ice – and as clumps that had dropped to the bottom of the deep sea. How could that have occurred? What had happened in the weeks before?

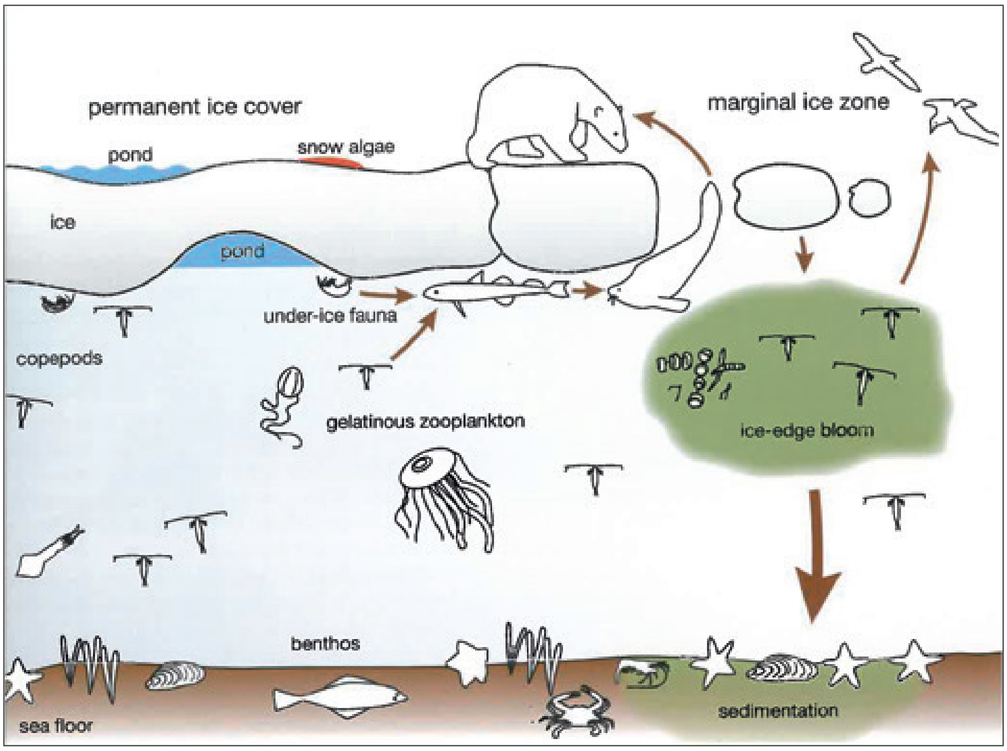
The large amount of sunlight that had penetrated through the ice had initially generated mega-growth of the ice algae on the bottom of the ice. When the sea ice then gradually melted in the course of the summer, the carpets of algae detached themselves, formed clumps and dropped like stones to the depths, i.e. unexpectedly quickly for the biologists. Once they reached the seafloor, bottom dwellers like sea cucumbers and feather stars pounced on the many chunks of food. What a sudden surplus of titbits for the deep-sea species otherwise used to rather slim pickings. The animals ate so much that they were significantly bigger and became sexually mature earlier than in a previous summer with a thicker sea ice cover.

In addition, clumps of algae that the deep-sea dwellers left over were decomposed by oxygen-consuming

If you look at the Arctic pack ice from the bottom, you will discover ice algae such as *Melosira arctica*. These and other cryophilic algae start to grow after the end of the polar night when sunlight returns to the Arctic and thus also penetrates through the ice. When the ice then melts in the course of the summer, the algae die. (Photo: ROV/AWI)



Two sea cucumbers head for a clump of algae that dropped to the Arctic depths from the surface. AWI researchers observed such a rain of food from above for the first time in summer 2012. They concluded that changes in the sea ice have a direct impact on the dwellers of the deep, too. (Photo: Antje Boetius/AWI)

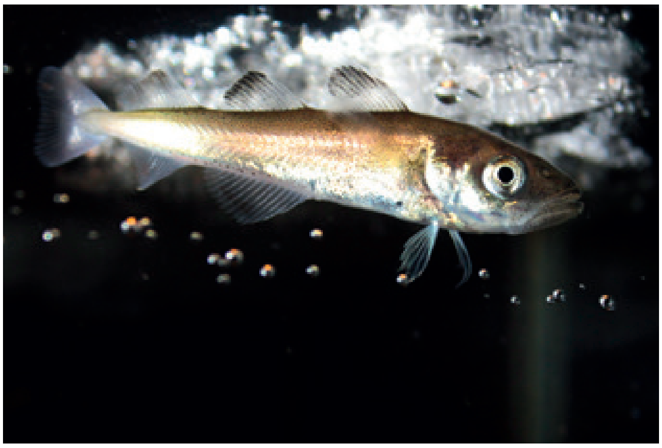


Nothing doing without ice
The ice cover of the Arctic Ocean is a major pillar of marine life. Its freezing and melting determine as of when and for how long polar bears can prey on seals on the ice. The same time is available to amphipods and copepods to eat their fill of ice algae on the bottom of floes. The well-nourished crustaceans serve, in turn, as food for polar cod which are hunted by seals, sea birds and whales.
When the ice area melts in summer, the larder of sub-ice species disappears as well. On the other hand, sunlight penetrates into the upper water layer. Algae start to grow, sink to the bottom and in this way supply the creatures of the deep sea with food. (Diagram: ArcCoML)

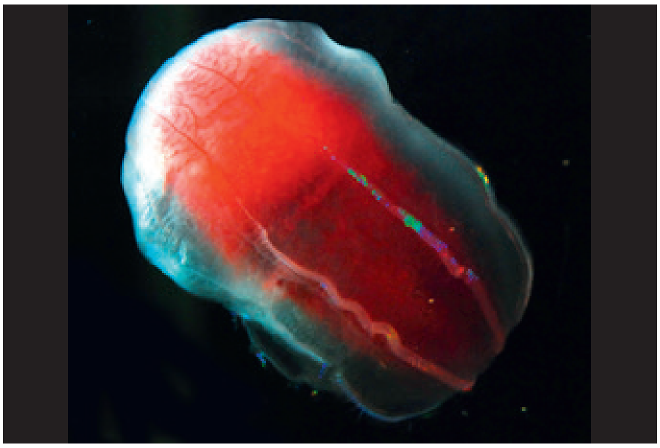
microorganisms. As a result of this, in turn, the oxygen concentration under the clumps of algae on the seafloor decreased considerably. In the end the AWI scientists gained the insight that the great amount of sunlight that had penetrated into the ocean had fundamentally altered the food structure of the Arctic Ocean from the surface to a depth of 4,000 metres – and had done so within a period of barely two months.

On future Polarstern expeditions AWI researchers will examine what long-term impacts the decline in sea ice has. One thing is already for certain: as sea ice disappears, so does an important element of its polar ecosystem (see diagram above).

In the short term the additional light will increase algae growth in the Arctic Ocean and thus the productivity of the water – depending on the question of whether sufficient nutrients are available to the algae. In the long term, however, the habitat of all those species that have adapted to the special challenges of life on, in and under sea ice will vanish.



The nursery grounds for the polar cod *Boreogadus saida* are disappearing along with the pack ice. Its offspring live in and under the ice up to the age of two. The fish find adequate food and refuge from enemies in the cavities and passageways. (Photo: Hauke Flores/AWI)



The Arctic ctenophore *Beroe cucumis* hunts under the ice. It feeds on other ctenophores, which in turn prey on amphipods and copepods that live on the bottom of the ice. The animal photographed here is about five centimetres long. (Photo: Carmen David/AWI)

At home in the far north: the beluga whale is one of 16 mammal species that live under or on the Arctic ice. (Photo: Franco Banfi)

What lives in the Arctic Ocean and what species need sea ice?

On, over or directly under the ice

- Around 60 different species of sea birds, such as the Atlantic puffin, fly over the Arctic Ocean in search of food.

- Today researchers know of 16 mammal species that live on or under the ice. The best known representatives are polar bears, ringed seals, walruses as well as bowhead whales, beluga whales and narwhales.

- A highly specialised community of more than 2,100 known unicellular organisms, such as viruses, bacteria, archaea and ice algae, as well as over 50 species of tiny creatures like amphipods and copepods, live in and on the bottom of the ice. Most algae grow in spring in the lower part of the ice where the temperature is constant and the nutrient density is the highest. Bacteria, by contrast, can withstand temperatures down to minus ten degrees Celsius and populate the entire ice.

In the water column

- Around 240 known species of fish live in the Arctic Ocean, of those the Arctic cod Arctogadus glacialis and the polar cod Boreogadus saida in particular are dependent on the ice. Their offspring find food and refuge on the bottom of the ice.

- When sea ice begins to melt in April, the more than 1,800 known species of Arctic phytoplankton, half of them diatoms, grow and reproduce. Their growth is so pronounced that a so-called algal bloom may occur off the edge of the ice, where around 340 zooplankton species, such as amphipods and copepods, then build up their fat reserves for the next winter.

On the seafloor

- In the shallow coastal waters of the Arctic seas researchers have discovered more than 160 different seaweed species. 40 percent of them are brown algae, 30 percent red and 30 percent green algae.

- Life on the bottom of the shallow Arctic shelf seas is composed of over 2,600 different species, primarily including crustaceans and annelids. For this reason, too, these areas of the Arctic Ocean are major feeding grounds for mammals like seals and whales.

- More than 1,100 animal species live on the bottom of the Arctic Ocean. The currently known species include 366 different arthropods, 197 Foraminifera species as well as 194 annelid and 140 nematode species.

The shells of the subarctic sea butterfly Limacina helicina barely measure a millimetre. AWI biologists are currently studying their reactions to climate change for two reasons. Firstly, invasive species are pushing into their habitat and, secondly, there is a risk that the animals may not be able to form enough building material for their shells due to increasing ocean acidification. (Photo: Kathrin Busch/AWI)

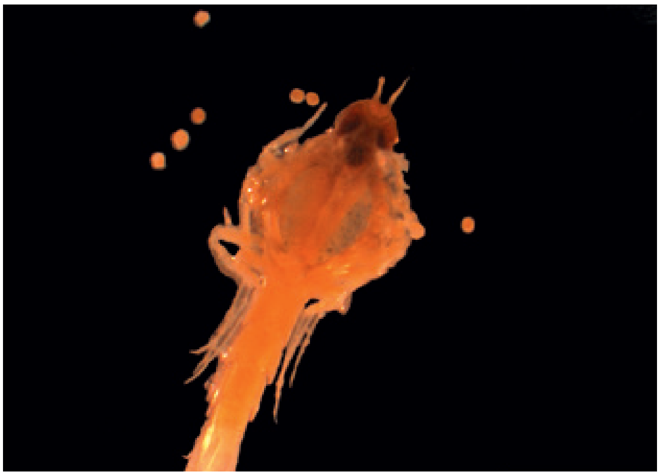
Fram Strait: Highway for species migration

In the course of climate change the Fram Strait has become a highway for species migration. Atlantic water masses that are warmer than two degrees Celsius have always been flowing into the Arctic Ocean through the marine passage between Greenland and the Spitsbergen island group. In the past decades, however, the temperature of this inflowing water has risen constantly. As a result, the central Arctic waters are warming and, in addition to that, the warm inflow opens the way into higher latitudes for invasive species from the Atlantic – such as the sea butterfly Limacina retroversa and the amphipod Thermisto compressa.

Both Atlantic dwellers like it warm. The sea butterfly Limacina retroversa, for instance, feels most comfortable at a water temperature of 2 to 19 degrees Celsius. Up to 15 years ago scientists at the Alfred Wegener Institute found them only occasionally at the HAUSGARTEN, the deep-sea observatory for long-term studies in the Fram Strait. Their subarctic relative Limacina helicina fell into their trap much more often back then. This cryophilic sea butterfly reproduces best at temperatures from -1.6 to 4 degrees Celsius and has numbered to date among the most important animals of prey for fish and baleen whales in the Fram Strait.

However, the Arctic sea butterfly has had to share its territorial supremacy since 2005. At that time significantly warmer Atlantic water than in the years before flowed into the Fram Strait – and with this flow came the Atlantic relative.

AWI scientists cannot yet say whether the invasive species will completely drive out the native species. In any case, if the temperature of the water flowing northward continues to rise, Limacina helicina might lose its home match against the Atlantic sea butterfly and migrate to the north. The reason: In the long term it does not tolerate the heat as well as its adversary from the south.



This female Atlantic amphipod had a bulging pouch filled with eggs (spherical shape) when it got caught in the trap at the deep-sea observatory. Finds like this one are evidence that the invasive species have made themselves at home in the Arctic. (Photo: Angelina Kraft/AWI)

Small replaces big: This picture shows the differences in size between the Arctic amphipod *Themisto libellula* (top), its subarctic relative *Themisto abyssorum* (middle) and the Atlantic migrant species *Themisto compressa*. (Photo: Angelina Kraft/AWI)

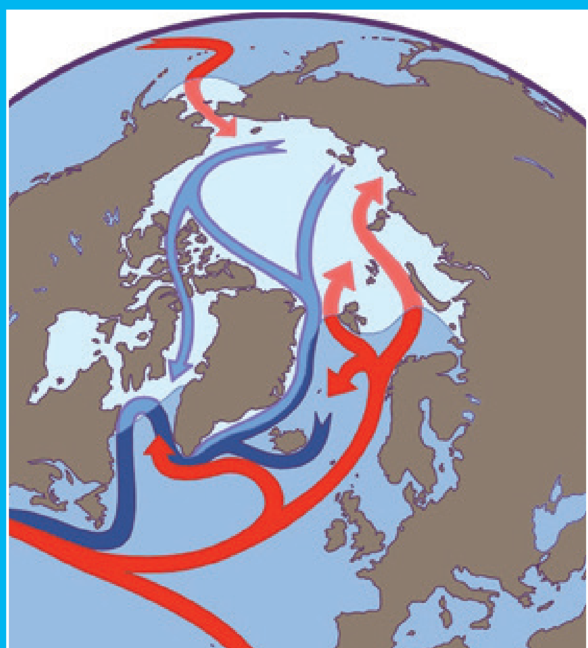
The amphipod Themisto compressa is one step further than the Atlantic sea butterfly. It, too, came to the Fram Strait with the warmer Atlantic water. In contrast to the sea butterfly, however, it has now managed to reproduce in the far north, too, as AWI biologists just recently found out.

In the end the victims of this increasing species migration from the North Atlantic to the Arctic Ocean will presumably be the animals at the end of the food chains. After all, many of the Atlantic invasive species are significantly smaller and thus less nourishing than their subarctic and Arctic relatives.

One example: Fish, seals, sea birds and whales that used to prey on the Arctic amphipod Themisto libellula in the Fram Strait captured around 40 milligrams of fat in each adult amphipod. A genuine feast! To get the same amount of energy from their new prey, the Atlantic amphipod Themisto compressa, substantially more hunting perseverance is necessary. The reason is that an amphipod of this species has a maximum length of 2.5 centimetres and contains no more than three milligrams of fat. That means the Atlantic cod and its fellow species have to catch about twelve times more of the new amphipods than before.

The heat pathway

The Arctic Ocean is linked to the other oceans of the world via several seaways. The seaway through the Bering Sea connects it to the Pacific. There warm water having a temperature of -1.6 to 2 degrees Celsius, depending on the season, flows into the Arctic Ocean. The link to the Atlantic Ocean runs via several accessways, including through the Fram Strait, the passage between Greenland and Spitsbergen.
West and east of Greenland water that may be -1.9 degrees cold flows from the Arctic Ocean to the south. On the eastern side, by contrast, water that is more than 2 degrees warm flows from the Atlantic Ocean to the north via two ways (Fram Strait and Barents Sea) – and the volume is ten times that on the Pacific side. Around half of that turns around immediately in the Fram Strait. The other half, however, reaches the far north. AWI scientists have been measuring the temperature of the Atlantic water flowing through the Fram Strait for over 15 years. It has risen by half a degree Celsius since the beginning of the measurements. That means the Atlantic flow now carries more heat to the Arctic Ocean than before and thus couples it to the great heat store of the "seven seas".



This map shows the seaways via which warm water (red) flows into the Arctic Ocean and where cold water (blue) flows out. (Graphics: NSIDC)

Clear signs: The Kongsfjord on Spitsbergen displays a different picture today than three decades ago. Thirty five years ago the fjord was frozen over around 200 days a year and covered with sea ice. Now the ice cover does not form until much later in the year and holds for a maximum of 40 days. In the same period (1980-2010) the average temperature on the water surface rose from 1.7 to 2.2 degrees Celsius. (Photo: Joe Haschek/AWI)

Fjords on Spitsbergen: Adaptable generalists wanted

Species that once wanted to survive in Spitsbergen's fjords had to be perfectly adapted to the ice-cold living conditions. Specialists like the polar cod were required. In the course of evolution, for example, it developed antifreeze proteins to be able to survive in the surface water of the Atlantic Ocean that could reach minus 1.8 degrees. It found protective nursery grounds for its offspring in the pack ice and specialised in prey that was available in ample amounts in the Arctic Ocean. This art of adaptation was rewarded with a leading role as a "key species" in the Arctic food web. Down to today polar cod is the most important animal of prey for Arctic mammals like seals and beluga whales and is also fished in large volumes by people.

Now, however, this leading role is at stake. The rising temperature of Arctic waters takes a lot of energy out of the polar cod. Laboratory experiments at the Alfred Wegener Institute have shown that it is too warm for the fish even in water that is four degrees Celsius and it does not grow as well as at a temperature around the freezing point.

On the other hand, its relative, the Atlantic cod, feels really comfortable at four degrees Celsius. It has migrated from the increasingly warmer North Sea and North Atlantic to the north in the past years and now finds optimal living conditions in Spitsbergen's fjords. Its secret of success: The Atlantic cod is a generalist. It feels good at a water temperature of four to ten degrees Celsius and can quickly adapt its metabolism, blood circulation and other bodily functions to changing living conditions. Likewise it can presumably cope with the increasing stress due to the acidifying water of the Arctic more easily than the polar cod. AWI experts therefore assume that the resistance to ocean acidification and the simultaneous

The Atlantic cod – photographed here in an aquarium – has migrated from the North Atlantic to the Arctic in recent years and is competing with its cryophilic relative there, the polar cod, for the territory in Spitsbergen's fjords. (Photo: Hans-Petter Fjeld (CC-BY-SA))

As a fully grown crab, the cryophilic spider crab *Hyas araneus* can cope with acidified water. It gets extremely critical, by contrast, if the crab encounters water masses with increased acidity as a larva. (Photo: Lars Harms/AWI)

rise in temperature could be a decisive factor in the competition between the two species.

However, ocean acidification can also impair generalists. The way in which this happens is something the offspring of the spider crab *Hyas araneus* will presumably get a taste of. In contrast to the fully grown members of their species, the spider crab larvae swim in the upper water layers, i.e. where, according to scientists, ocean acidification will first make itself felt.

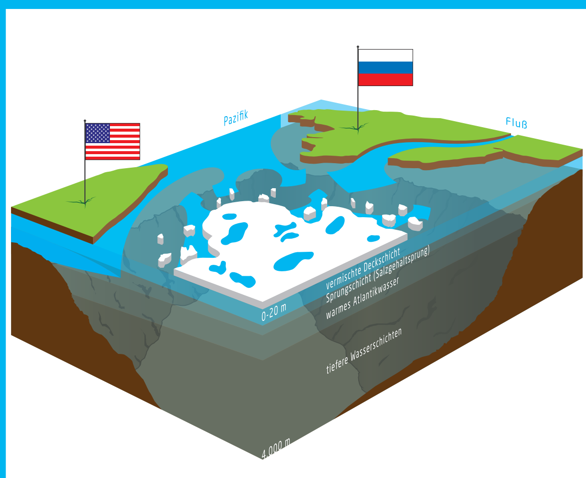
AWI biologist have simulated the future living conditions of spider crabs in the laboratory and determined that more acidic seawater influences the development of the crabs even in the egg. It alters the acid content of their blood and other body fluids and thus has a very decisive impact on the offspring's chances of survival. In laboratory tests over 70 percent of the larvae that were exposed as embryos to acidic water died in the egg.

But that's not all. If the offspring withstand the acid stress as embryos and hatch as larvae, they immediately face the next challenge. This is due to the fact that spider crab offspring develop at a slower rate in more acidic water. They thus run the risk of being eaten and, in addition, react sensitively to increasing temperatures. If the larvae also survive these tests, however, they are out of the woods, so to speak. They settle on the seafloor. Their body is fully developed and from then on can adjust better to more acidic water.

A cover of freshwater

Some of the biggest rivers on our planet, such as the Lena and the Mackenzie, flow into the Arctic Ocean. They transport lots of freshwater that mixes with seawater on the surface, forming a low-saline layer which lies like a lens on the deeper water layers. There are indications that precipitation in the Arctic and in the large water catchment areas of the rivers has increased in the course of climate change and that the rivers transport more freshwater to the ocean today than 20 years ago. In addition, the freshwater input due to melting sea ice is growing.

AWI oceanographers and their international partners have observed a drastic "freshening" of the Arctic Ocean in the past 25 years. Today the Arctic Ocean stores 30 percent more freshwater in its upper water layer than in 1992. Whether the increased inflow outlined above is the reason for this or whether the discharge of the low-saline water (or of freshwater) towards the Atlantic was reduced has not been clarified yet. In any case the freshening leads to a more stable density stratification of seawater that prevents the exchange between the upper layers suffused with light and the high-nutrient deeper layers.



This graphic illustration shows from what sources freshwater and lower-saline water enter the Arctic Ocean (rivers, melting sea ice, Pacific). Moreover, it illustrates how the layers of the water masses form according to salt content. The freshwater that has flowed in is primarily found in the top layer that lies like a cover on the layers with higher salt concentration. (Graphics: AWI)

Interdisciplinary cooperation on the ice: biologists, sea ice physicists and chemists of the Alfred Wegener Institute investigate sea ice in the central Arctic Ocean on a summer expedition of the research vessel Polarstern in 2012. (Photo: Mar Fernandez, AWI)

Research questions: Understanding the big picture

Warmer, more acidic, less ice: the changes in the Arctic Ocean are advancing at a rapid pace. To be able to understand them and assess the consequences for the rest of the world better, scientists from all disciplines represented at the Alfred Wegener Institute have joined to form an interdisciplinary sea ice team. Together the researchers want to examine the complex interplay between atmosphere, ice, ocean and land.

This cooperation not only involves a regular exchange regarding new findings and research methods, but also jointly planned Polarstern expeditions to the central Arctic Ocean. To understand how climate change is altering the Arctic from the atmosphere to the deep sea, physicists, biologists, geologists, chemists, oceanographers, meteorologists and many other specialists are working hand in hand at AWI.

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