CHANGING ARCTIC OCEAN

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CHANGING ARCTIC OCEAN

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Editorial – Changing Arctic Ocean

By: Roxana Suehring, Kirsty Crocket, Penelope Lindeque & Christian Maerz

The Arctic is the most northern part of our Earth. For many of us the Arctic is a faraway place, a place of stories, adventures, mysterious and beautiful phenomena like the Northern Lights, and majestic animals like the polar bear. But the Arctic is also a home; to animals large and small as well as people. Moreover, even though the Arctic might seem very far away to most of us, the thing that happen there can have an impact on the entire Earth. This is what the research we are presenting in this collection is about – the enormous difference tiny animals, plants, and even gases in the Arctic can have and why we should all care about what is happening in that beautiful snow-covered world far in the North.

To give you a little bit more background information: The Arctic is huge, but it is not its own continent or country. It actually spans over several countries, including Canada, Denmark (Greenland), Finland, Iceland, Norway, Sweden, Russia, and USA. However, the largest part of the Arctic is not land but is water – the Arctic Ocean.

For hundreds of thousands of years, large parts of the Arctic Ocean were covered by ice all year round. Many animals, such as polar bears, Arctic foxes, seals, fish and birds and even some people have made this icy place their home. They have learned to live with the ice, and some plants and animals even need it to survive.

But recently, things in the Arctic have been changing. You have probably already heard a lot about climate change. Climate change impacts the long-term weather (climate) everywhere on our planet. Many areas are getting warmer, some might get colder, and everywhere we see more extreme or unusual weather, such as storms, floods or droughts. But nowhere is climate change happening as fast as in the Arctic.

Now you probably ask why it is so bad that the Arctic is getting a bit warmer. That should make it a nicer place to live, right? For some animals and plants, you are right! The warming waters of the Arctic Ocean have made it a more welcoming place for some fish species and zooplankton that usually live further south1,2. But, unfortunately, the warmer temperatures are not beneficial for everything. As the water and the air get warmer, the ice that has covered the Arctic Ocean for all this time is melting in summer, and not growing back as much as it used to in winter. This is a problem for animals like polar bears, who need the ice as a hunting ground. But, even more important, this is a problem for many tiny organisms that live inside and under the frozen seawater3,4. These tiny plants and animals in the ice are the food source for many other animals in the Arctic5 and without them neither fish, nor seal, nor Arctic foxes, nor even polar bears can survive in the Arctic6,7.

Scientists from across the world are working hard to better understand what is happening in the Arctic because of climate change. Using data from expeditions into the Arctic, computer analysis, and even satellites8, scientists are cracking the code of Arctic climate change9, helping to understand the impact of climate change on Arctic communities, animals, and our global climate7,10.

Often these studies seem very specialised, focusing only on the tiny algae or the chemical elements – but such detailed studies are needed, like tiny pieces of a jigsaw puzzle, to build a complete picture of the changing Arctic. For example, by measuring the fat in algae and zooplankton in Arctic animals, scientists discovered that these tiny plants and animals are the basis for the entire Arctic food web6. This means that climate change will not only impact the tiny creatures living in the ice, but also fish and even mammals that prey on the fish – such as seals and polar bears7, 11.

At the same time, climate change also makes a difference to where the water of the Arctic Ocean is coming from: more water is coming from the Pacific Ocean and the Atlantic Ocean at the same time. This is important, because not all seawater is the same. Some is very nutritious and helps plants and animals grow, while other water does not contain many nutrients and makes it hard for plants and animals to survive. Climate change has led to both nutrient-rich water from the Pacific Ocean and nutrient-poor water from the Atlantic Ocean to flow more quickly into the Arctic. We are not sure yet whether that will lead to more nutrients – and therefore more plants and animals – in the Arctic Ocean or to less12.

But why would that be a problem for anyone outside the Arctic? One reason is that tiny gases can make a big difference to the climate – especially in the Arctic, but also beyond. Carbon monoxide (CO) and dimethylsulfide (DMS) are two of these gases that can warm (CO) or cool (DMS) the Arctic climate13. The Arctic Ocean produces both of these gases and they are not the only climate-relevant tiny gases the Arctic Ocean deals with: The Arctic Ocean and the muddy deposits at its bottom are an effective storage space for carbon dioxide (CO_2) – the gas everybody talks about when they talk about the reasons for climate change. Researcher have found that the water and the sea ice of the Arctic Ocean can filter CO_2 out of the air14. It is not clear yet how climate change will affect the storage of CO_2 in the Arctic Ocean. Less sea ice might lead to more algae that can take up CO_2, especially if the Pacific provides more nutritious water – but the loss of sea ice with all of its tiny inhabitants can also lead to less CO_2 storage15, 16. What we do know is that the outcome will not only affect the climate in the Arctic but have an impact on the climate around the Earth17.

Another reason everybody should care about what happens in the Arctic is the fact that if something we do can impact a faraway place like the Arctic, it can impact places anywhere in the world. This is why researchers and policy makers get alarmed if chemicals are found in the Arctic that really shouldn't be there. If a chemical used in your phone, couch or computer at home can make it all the way to the Arctic – where else can it get to and what will its impacts be on local animals, plants, and people18?

Likewise, things that are in the Arctic don't always stay in the Arctic: the waters of the Pacific Ocean and the Atlantic Ocean circulate around the Arctic and mix with the cold Arctic water. This leads to enormous currents of water that transport cold water away from the Arctic19. The Arctic water helps keeping our climate cooler – countering climate change, but it also enables warm water sea currents like the Gulf Stream that keep Europe warm14.

As you can see, the Arctic Ocean, its ice, tiny inhabitants and even chemicals are important for all of us. Let's start telling their stories and work together to keep the Arctic and all of our planet safe.

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THE EARTH AND ITS RESOURCES
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THE FUTURE OF THE ARCTIC: WHAT DOES IT MEAN FOR SEA ICE AND SMALL CREATURES?

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YOUNG REVIEWERS

ST. MARGARET'S CE JUNIOR SCHOOL
AGES: 9–10

The warming of our planet is changing the Arctic dramatically. The area covered by sea-ice is shrinking and the ice that is left is younger and thinner. We took part in an expedition to the Arctic, to study how these changes affect organisms living in and under the ice. Following this expedition, we found that storms can more easily break the thinner ice. Storms form cracks in the sea ice, allowing sunlight to pass into the water below, which makes algal growth possible. Algae are microscopic "plants" that grow in water or sea ice. Storms also brought thick heavy snow, which pushed the ice surface below the water. This flooded the snow and created slush. We discovered that this slush is another good habitat for algae. If Arctic sea ice continues to thin, and storms become more common, we expect that these algal habitats will become more important in the future.

INTRODUCTION

Arctic sea ice is the layer of frozen water covering the northernmost ocean on our planet. **Sea ice** moves constantly in response to **ocean currents** and winds, and is also sensitive to changes in temperature. It used to be several meters thick and would only partly melt in the summer. With the current increase in temperatures due to climate change, more and more ice melts over the summer. This means that now a larger part of the ice cover is young and thin, because it only had one winter to grow [1]. These changes have consequences for the climate system and for organisms living in the Arctic Ocean (reviewed in [1]). For example, changes in the ice thickness affect the amount of sunlight and heat that reaches the ocean. More heat accumulated in surface waters leads to less ice growth and further ice melt. More sunlight below the ice enables more algal growth in the ocean. Since **algae** are responsible for food production the same way as plants are on land, it is important to know how many and which type of algae will grow in the Arctic Ocean. This will help us to predict how other organisms, such as fish and sea birds will respond. In 2015, we took part in a research expedition in the Arctic to collect data that will help us address this challenge.

During the research expedition, a Norwegian research ship named Lance was anchored to sea ice exiting the Arctic Ocean (Figures1, 2A; [2]). The ship drifted with the sea ice for half-a-year, without using motor power. From January to June 2015, we used the ship as a base to carry out measurements of the atmosphere, ice, and ocean, such as temperature, snow depth, ice thickness, and the amount and type of algae present (Figure 2). Our measurements from the expedition taught us about new features emerging in the Arctic Ocean as a consequence of ongoing climate change. To learn more about the project go to our webpage www.npolar.no/nice2015 or look for the hashtag #nice2015arctic on social media. Here we will explain our findings on how changes in sea ice affect the "home" of algae, the sea ice, and underlying ocean **habitats**.

WHAT MAKES THE ALGAE GROW WHERE THEY GROW?

We, the sea ice biologists, were especially interested to study the algae. Almost all food in the ocean is produced by algae, which are capable of producing organic sugars using sunlight, just like land plants do. This process is called **photosynthesis**. In the water column and inside the sea ice, the algae are microscopically small and are called phytoplankton and ice algae, respectively.

In spring, we were surprised to find high amounts of phytoplankton growing in the water under the sea ice [3]. Typically, very little sunlight reaches the water below the sea ice, because it is reflected away by the white ice and snow. Most of the phytoplankton present were of

ARCTIC

The Arctic is a polar region located at the northernmost part of the Earth, often defined as the region north of the Arctic Circle (66° 33′N). Around 60% of the Arctic is sea, much of which is covered by year-round sea ice.

SEA ICE

Sea ice is frozen ocean water. It forms, grows, and melts in the ocean. In contrast, icebergs, glaciers, and ice shelves form on land and are made of fresh water from compacted snow.

OCEAN CURRENTS

Oceanic currents describe the movement of water from one location to another, similar to wind in the atmosphere. Ocean currents are driven by wind, water density differences, and tides. Ocean currents affect the Earth's climate by driving warm water from the Equator and cold water from the poles around the Earth.

ALGAE

Organisms that grow in the water and can fix carbon from the atmosphere like plants do on land. In the high Arctic, the algae present are tiny, single-celled organisms.

HABITAT

A place or area with certain environmental conditions, in which certain type of organisms live.

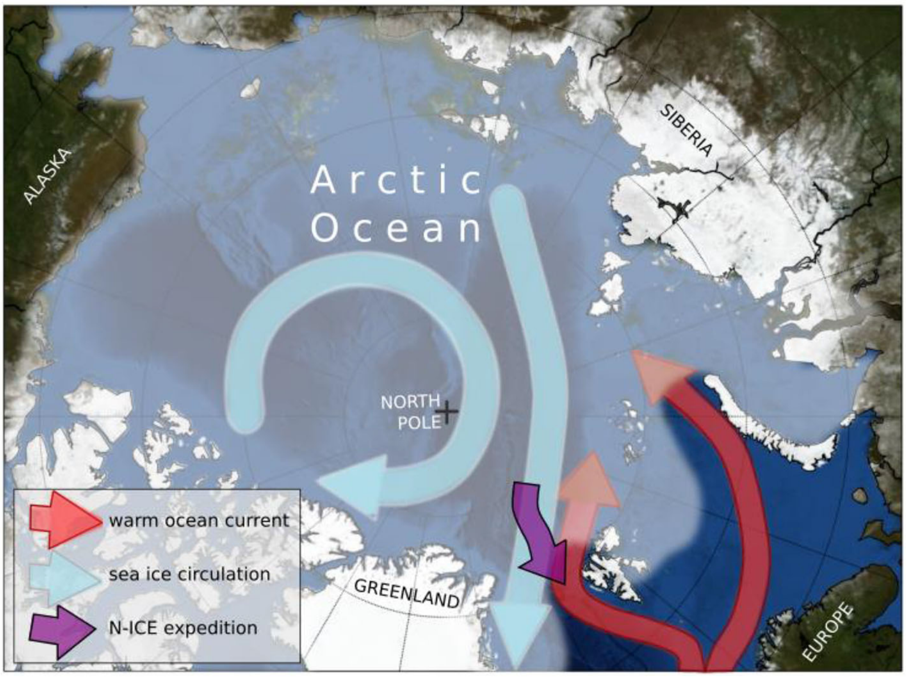

Figure 1

Figure 1

A map of the study area, with a drift track of the research ship Lance, sea ice movement patterns, and warm ocean currents indicated with arrows (see legend). The shaded area marks the usual extent of the sea ice cover. Image background is from Blue Marble Next Generation (NASA).

PHOTOSYNTHESIS

The process in which algae and plants convert, with the help of sunlight, inorganic carbon from the atmosphere or the water into organic compounds, such as sugars, that they use for growth. Other organisms rely on these sugars and other compounds for their food. In addition, oxygen is released in the process.

DIATOM

Type of single-celled algae that has a wall made out of a mineral called silicate, which is like glass. They are very abundant in the sea and important in the Arctic food webs. There are many different species of diatoms and they can be identified under the microscope.

the species *Phaeocystis pouchetii* (Figure 2D). This algae species is unicellular but the cells can connect together to form colonies, which are up to 0.2 mm in diameter and which are possible to see with your bare eye.

Later in spring, toward the end of our expedition, we found high amounts of algae on top of the ice, in a layer between the thick snow and the relatively thin ice cover (Figure 2E; [4]). Typically, the main habitat for ice algae is the bottom of the ice which interacts with sea water. When we analyzed these algal communities under a microscope, we found that they consisted of species that are typically found in the water column, such as chain-forming **diatoms** (Figure 2F). These species are not typical in the sea ice.

To find out how these algae ended up between the snow and ice and what made algal growth possible in these habitats, that is, the different types of "homes," we turned to our oceanography and sea ice physics colleagues to hear what had happened with the ice cover in the previous months (Figure 3).

STORMS BREAK UP ICE FLOES INTO SMALLER PIECES

Some of the most exciting processes we observed during our research expedition happened during several powerful winter storms. These storms came from the south and brought strong winds, rapid changes in air temperature, and heavy snowfall [5].

Figure 2

Figure 2

(A) Research ship Lance frozen in sea ice during the expedition. Some of our research equipment, such as tents and sledges, are visible around the ship. Photo: Seb Sikora. **(B)** During winter, the sun does not rise in the Arctic. The night continues for 24 h a day, and work must be completed in darkness. For example, it is hard to see polar bears! Photo: Jago Wallenschus. **(C)** Sea water sampling through a hole in the sea ice. Photo: Marcel Nicolaus. **(D)** Photo taken through a microscope of a colony of algae (*Phaeocystis pouchetii)* observed forming a bloom in the water under the ice. Photo: Jozef Wiktor. **(E)** Green and brown slush on the ice under the snow: this is algae! Photo: Hanna Kauko. **(F)** Microscopy picture of a diatom chain: This is the type of algae that we found in the slush. Photo: N-ICE2015 biology team.

The strong winds during the storms pushed the ice around and broke it into pieces, making it more fragile and deforming it, more like a boulder field [5]. This opened up areas of open water, known as leads. Eventually these leads were covered by thin ice, but they still let high amounts of sunlight pass through, compared with thicker ice covered in snow [6].

Connecting all our findings, we discovered that the leads enabled the algae to grow below the sea ice, by allowing the necessary sunlight to pass through for algal photosynthesis [3]. The algae we found, *Phaeocystis pouchetii*, can cope with changes between low light under the thick ice and high light intensity under the leads better than some other algae, which may explain its success under this type of ice [3].

Figure 3

Figure 3

During the expedition, we made many interesting biological findings. Observations of the physical processes in the atmosphere, snow, ice, and ocean during the winter helped to explain why the algae were growing in certain habitats. Photos that are used for the cartoon (in the order from 1 to 8): Paul Dodd, Polona Itkin, Paul Dodd, Seb Sikora, Mar Fernández-Méndez, Marcel Nicolaus, Mar Fernández-Méndez, Amelie Meyer.

HEAVY SNOW PUSHES THE ICE SURFACE BELOW WATER AND LETS IT FLOOD

Throughout our research expedition, our colleagues, the sea-ice physicists, found an unexpectedly deep layer of snow on top of the sea ice. This layer of snow was approximately half a meter thick. The snow accumulated on top of the sea ice during several storms earlier in the winter [5].

We found that the sea ice was very thin in relation to the deep snow layer. The fluffy texture of snow makes it a highly effective insulating blanket over the ice. This keeps the ice warm, compared with the cold atmosphere, and therefore prevents the ice from growing thicker during the cold winter.

On several occasions, we saw that the weight of the heavy snow pushed the surface of the ice below the water level. Imagine sitting on a swimming float in a pool. This caused the snow and ice to be flooded with seawater, which created a layer of slush. Together with the water, small amounts of algae were brought to the top of the ice. These algae acted in a similar way as seeds would and started an algal community in the slush layer, which explained our finding of the water column species. The slush creates a good place for algae to grow and reproduce, because there is more sunlight available than under the ice and there are less animals (zooplankton) eating them [4].

SEA ICE CAN ALSO MELT FROM BELOW

Melting of the ice can also make it thinner and lighter in relation to the snow cover and lead to surface flooding. In addition to being melted by sunlight in spring and summer, sea ice can melt from below even if the water is just a few degrees warm. During storms, the strong winds stir the ice and the ocean below the ice, mixing up warmer water from deeper layers to the surface where it melts the ice [7]. This is a special process that happens in certain parts of the Arctic, where warm ocean currents from the North Atlantic flow into the Arctic under the ice cover (Figure 1). This warm Atlantic Water is usually about 2°C, which is a few degrees warmer than freezing Arctic waters at −2°C. With global ocean warming, we can expect that at some point in the future, the ocean will be able to melt the sea ice from below even without the help of storms: warm Atlantic water under the ocean surface only needs to be as warm as 5°C to melt sea ice very effectively, without the extra stirring caused by storms [8].

CONCLUSIONS—WHAT WILL THE FUTURE ARCTIC LOOK LIKE FOR ALGAE?

We think that during our expedition we saw what lies ahead for new algal life in the Arctic. We know ice is getting thinner and thus snow cover may get thicker in relation to the ice. This could make the occurrences of slush layers more common and make it an important habitat for algae in the future. Deeper snow covers resulting from more frequent storms may also make it more common.

Winter storms are increasing in frequency and this is likely due to climate change. As the Arctic sea ice continues to thin, it is becoming more sensitive to these winter storms. We expect that the ice will break more easily and allow more sunlight to pass through in the future, which could make algae growth below the ice happen more often.

Our research helps to predict how the different parts of the Arctic sea ice cover respond to climate change and how the Arctic **ecosystems** may change as a consequence. Yet there are still several questions we have no answer to: for example, is this happening all around the Arctic already and how will it progress toward the North Pole? What will the ocean be like when all the ice has melted in the summer? What type of algae will live in the future Arctic? There is so much more to find out!

ECOSYSTEM

An ecosystem is a group or community of interconnected living organisms and their environment. Examples of marine ecosystems include coral reefs, deep sea, and of course Arctic ecosystems.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ST. MARGARET'S CE JUNIOR SCHOOL, AGES: 9–10
We are Jamie, Lauren, Vaishali, Hannah, Yasmin, Shreyan, and Avleen. We are all keen scientists and really had fun during the review process. We are proud that we are influencing how other children will learn, and our teachers said we returned to our classroom buzzing.

AUTHORS

HANNA M. KAUKO
Dr. Hanna Kauko is interested in the relationship between light and algae and how this affects primary production and light conditions in the ocean. She completed her PhD studies on this topic joining the N-ICE2015 campaign at the Norwegian Polar Institute. By using observations, she aims to understand microalgal ecology in the polar oceans and provide knowledge for modeling and management purposes. Currently she is a post-doc researcher at the Norwegian Polar Institute, working on Southern Ocean phytoplankton. *hanna.kauko@npolar.no; *hanna.kauko@alumni.helsinki.fi

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Dr. Mar Fernández-Méndez is an enthusiastic marine microbiologist who enjoys studying the role of algae in the world's oceans. After working in the Arctic for 7 years, including the N-ICE2015 campaign at the Norwegian Polar Institute, and investigating the effects of climate change on primary production in cold waters, she has now moved toward warmer waters to study the potential of phytoplankton to remove carbon from the atmosphere, thereby helping mitigate global warming. Her current position is based at GEOMAR Helmholtz Zentrum für Ozeanforschung in Kiel, Germany, and her field work takes place in Gran Canaria and Perú.

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AMELIE MEYER
Dr. Amelie Meyer is passionate about climate variability, polar science, and ocean circulation. Her work looks at how and why the polar oceans are changing, combining observations, reanalysis products, and climate models. Amelie has spent several months both in the Arctic and in the Southern Ocean collecting data to answer these questions, including taking part in the 6 months-long N-ICE2015 expedition in 2015 while working at the Norwegian Polar Institute. She currently works for the ARC Centre of Excellence for Climate Extremes based at IMAS, at the University of Tasmania in Australia.

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ANJA RÖSEL
Dr. Anja Rösel completed her PhD in polar remote sensing, studying the sea ice from satellite images. To learn more about the processes in reality, she decided to apply for a position with more field work at the Norwegian Polar Institute. There she got the opportunity to join the N-ICE2015 expedition. Currently she works at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany, and analyzes satellite images using artificial intelligence.

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POLONA ITKIN

Dr. Polona Itkin is intrigued by the recent changes in how the Arctic sea ice moves. While the reasons for this lies in the atmosphere, ocean, and in the thinner ice itself, new motion patterns also influence all the boundary layers. The N-ICE2015 teamwork, achievements, and the remaining research challenges inspired her to join the next large Arctic research project—MOSAiC (https://www.mosaic-expedition.org). As part of this expedition, Polona will explore the role of deformed ice (pressure ridges and leads) for snow accumulation. She is currently a research scientist at the UiT, The Arctic University of Tromso and an associate of the Colorado State University, Fort Collins, CO, USA.

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ROBERT M. GRAHAM

Dr. Robert Graham is a climate scientist with a passion for ice. His research focuses on the Arctic Ocean as well as the Southern Ocean around Antarctica. He has used observations, and climate models to explore ongoing climate change in these regions, as well as past and future changes on timescales of tens to thousands of years. Robert worked as a post-doc at the Norwegian Polar Institute on the N-ICE2015 project from 2015 to 2019. He is now investigating how long-term weather forecasts can be used to manage hydropower resources in Scotland at Strathclyde University, Glasgow.

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ALEXEY K. PAVLOV

Dr. Alexey K. Pavlov is an interdisciplinary researcher trying to understand the big changes that are happening in the Arctic Ocean and its ecosystem. He is particularly interested in the fate of sunlight in the Arctic Ocean and sea ice, and the many connections that light has with physical, biogeochemical, biological processes, and living organisms in the Arctic. As a post-doctoral researcher at the Norwegian Polar Institute, Alexey was lucky to join the N-ICE2015 expedition. He is currently a scientist at the Institute of Oceanology of the Polish Academy of Sciences (Sopot, Poland) and Akvaplan-niva (Tromsø, Norway).

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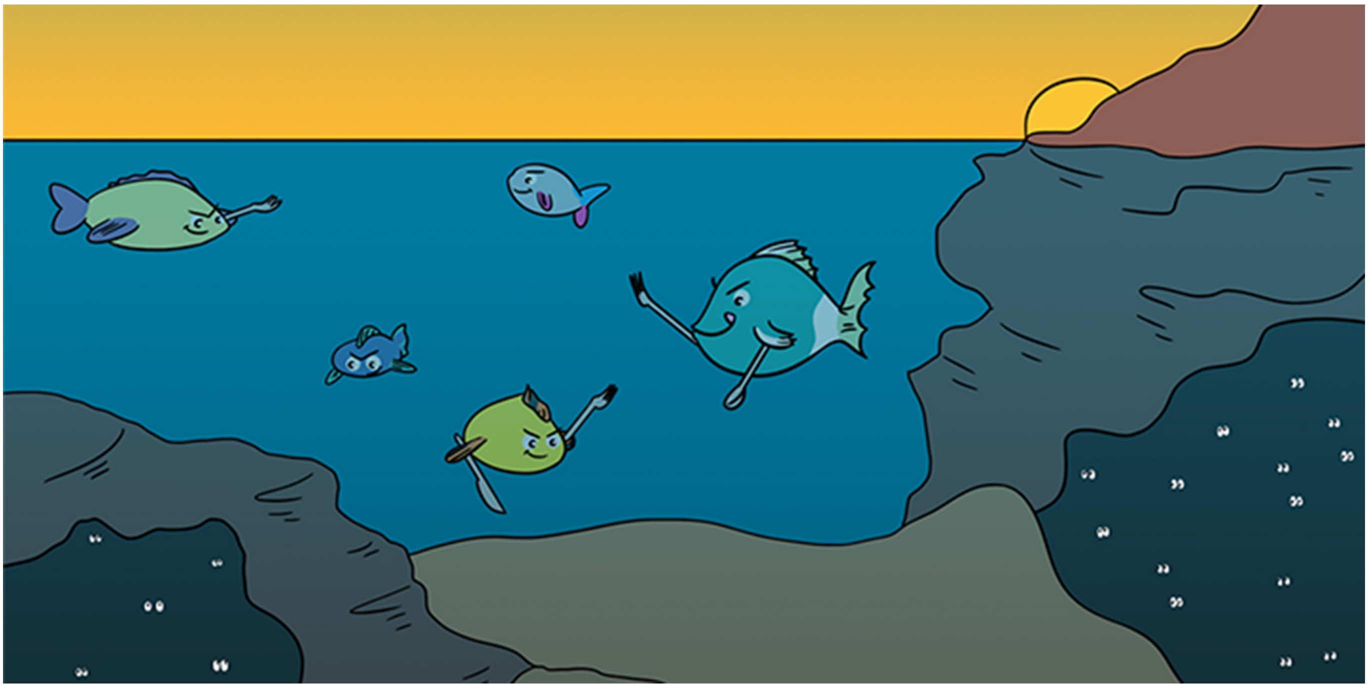

DVM: THE WORLD'S BIGGEST GAME OF HIDE-AND-SEEK

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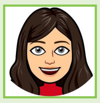

GEMMA
AGE: 16

Diel vertical migration (DVM) refers to the daily, synchronized movement of marine animals between the surface and deep layers of the open ocean. This behavior is the largest animal migration on the planet and is undertaken every single day by trillions of animals in every ocean. Like a big game of hide-and-seek, animals that perform DVM spend the day hiding from predators in the deep ocean, and then migrate to the surface to feed under the cover of darkness. In this article we will explore this incredible strategy for survival. We will introduce the animals involved, describe how the environment of the open ocean drives DVM, and reveal the questions still to be answered as the ocean environment continues to change.

WHAT IS DIEL VERTICAL MIGRATION?

Flocks of birds flying south for the winter and giant herds of wildebeest searching for green pasture in the Serengeti are some familiar examples of animal migrations. **Diel vertical migration (DVM)** is less well-known but we think you will find it equally fascinating. DVM describes the synchronized movement of marine animals between the surface and deep layers of the open ocean. This behavior takes place every day, in every ocean, and by biomass it is the largest migration on the planet!

To better understand this behavior, let us separate DVM into its separate words. *Diel* means that it occurs on a daily, 24-h cycle. *Vertical* refers to the direction of the movement up and down in the water column, generally between the surface layer (called the **epipelagic** layer) and the deeper, middle layer (called the **mesopelagic** layer). That covers a distance of up to 1,000 m and for the small, oceanic animals called **zooplankton** that perform DVM, this is an impressive journey;

"It is an enormous movement on their scale. If you scaled it to a human, that would be like running a 10K to get your dinner and then a 10K before you went to bed, and doing it at twice the speed of an Olympic marathon runner," said Senior Scientist Kelly Benoit-Bird from MBARI[1].

Finally, *migration* tells us that this is a mass movement of animals. In fact, by biomass (the total mass of animals in a given area) it is considered to be the largest migration of animals on the planet. For example, just the small migrating fishes have an estimated global weight of more than 1,000 million tons [1]! The word migration also gives us a clue that DVM is not random or done for fun, but that it serves an important purpose—to help the animals survive.

WHY DO ANIMALS DO THIS?

So, how does a daily marathon of such distance help these animals to stay alive?

Let us set the scene. In the ocean, light changes through the water column, creating sunlit surface water and dark deep water. This light also changes throughout the day. These light conditions, changing in both depth and time, are important for driving DVM behavior.

Zooplankton are bite-sized, energy-rich snacks for many **predators**, such as fish, whales, and seabirds. These predators are fast and use their eyes to detect their food, which means that they are most effective at hunting during the day and in the sunlit surface water. However, the zooplankton's food source, tiny plants known as **phytoplankton**, are also only found in the surface water.

So, the zooplankton face a dilemma: if they stay in the surface waters to feed, they risk being eaten. If they hide in the deep, they will be

DIEL VERTICAL MIGRATION (DVM)

The daily, synchronized movement of marine animals between the surface and deep layers of the ocean.

EPIPELAGIC

The surface layer of the open ocean between 0 and 200 m deep. In this layer there is enough light for phytoplankton to grow.

MESOPELAGIC

The middle layer of the open ocean between 200 and 1,000 m deep. Light rapidly declines in this layer and is often called the "twilight zone."

[1] www.mbari.org/canon-spring-2019/ (accessed June 26, 2019).

ZOOPLANKTON

A diverse group of marine animals that are mostly microscopic in size, but can include jellyfish and the eggs of larger animals. Zooplankton can swim or propel themselves to find food and mates locally, but can only travel large distances across the sea by drifting with the currents.

PREDATOR

An animal that obtains food by hunting and consuming other animals.

PHYTOPLANKTON

Microscopic marine plants that are the base of the food chain in the sea. Just like plants on land, phytoplankton require sunlight in order to live and grow.

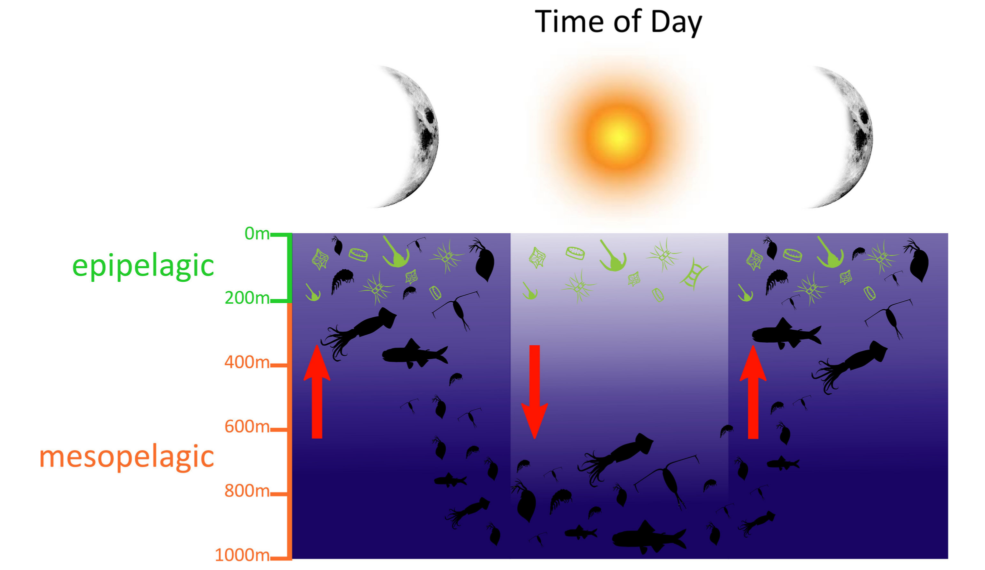

Figure 1

Figure 1

Light, food, and predation risk drive diel vertical migration (DVM) of zooplankton and fishes. When it is dark, zooplankton and small fishes rise to feed in the epipelagic waters under the cover of darkness. When it is light, they migrate back to the safety of the darker mesopelagic depths. Animals and phytoplankton are not drawn to scale.

safer, but soon starve. This is what we call a tradeoff: each option (to feed or to hide) brings with it a gain, but also a cost. DVM is the zooplankton's clever solution to balance this tradeoff and have the best of both [2].

Much like a game of hide-and-seek, the zooplankton remain in the deep, dark waters during daylight hours, out of sight of their predators. Under the cover of nightfall, they migrate upwards from the mesopelagic layer to the epipelagic layer, where they can graze in the relative safety of darkness at night (Figure 1).

WHEN DO OCEAN ANIMALS MIGRATE THIS WAY?

Zooplankton want to feed for the longest time possible, but they also want to avoid the surface during daylight. As a result, they have finely tuned their migrations to the timing of sunrise and sunset—migrating up when the sun sets and migrating down when the sun rises (Figure 1).

Because of the seasons, the time of up- and down-migrations changes through the year. In spring and autumn, day and night last about 12 h each across most of the planet. But in winter, the days are very short and the nights very long, meaning that sunrise is much later, and sunset is much earlier, with the opposite occurring in summer. We see these changes reflected in the timing of zooplankton migrations.

An exception to this rule is at high latitudes—the Arctic and the Antarctic. Here, the seasons are so pronounced, and the days become so short in the winter, that daylight fails to exist for months at a time. During this period, called the polar night, it is dark 24 h a day. So,

Figure 2

Figure 2

Examples of zooplankton and fish groups that live in the mesopelagic zone and may perform DVM: **(A)** sea butterfly (credit: R. Hopcroft, NOAA); **(B)** copepod (credit: U. Kils); **(C)** siphonophore (credit: K. Raskoff, NOAA); **(D)** amphipod (credit: E. A. Lazo-Wasem); **(E)** Hatchetfish feeding on a crustacean (credit: F. Costa); **(F)** glass squid (credit: E. Widder, NOAA); **(G)** comb jelly (credit: A. Semenov); **(H)** decapod (credit: S. Fielding); and **(I)** dragonfish (credit: E. Widder/HBOI, NOAA).

what do the zooplankton do? We used to think that they went into hibernation at this time. But recent research has shown us that some stay awake right through the winter [3]. Instead of migrating in time with the sun, they start to migrate in response to moonlight [4].

WHICH OCEAN ANIMALS PERFORM DVM?

When we use the word zooplankton, we are really referring to a hugely diverse group of animals. They can vary in size from less than a millimeter long to much larger examples, such as jellyfish. Zooplankton can look very different from each other, but they are united by the definition that, although they are able to weakly swim or propel themselves in the water column, they can only travel large distances across the sea by drifting with the currents. Some examples of zooplankton can be seen in Figure 2.

Zooplankton are really important for our ecosystems. Many zooplankton eat phytoplankton and turn this into an energy source. When the phytoplankton-eating zooplankton are eaten themselves, the energy from the phytoplankton becomes available to bigger zooplankton, fish, and even whales. So, DVM affects animals far higher up the food chain than just the zooplankton themselves. It is not just zooplankton that perform DVM. DVM has been seen in fish, and even some sharks perform a version of DVM. So, this is not one simple game of hide-and-seek. It is zooplankton hiding from their predators (such as small fish), who are also doing DVM to hide from their predators (big fish). And this massive game is happening every night, right beneath the waves.

WHERE DOES DVM OCCUR?

If you look in any sea, ocean, or lake across the planet at any time, you will find animals doing DVM. At sunset every night, they swim to the surface and, at sunrise, they sink to depth. DVM happens everywhere! The exact timings change. Away from the equator, the days are longer in summer and shorter in winter, and the timings of the migrations reflect this. At the equinoxes, on 21st of September and 21st of March, day length is consistent right across the planet. In theory, all the migrators should be swimming to the surface at about 6 o'clock in the evening. As the earth rotates and the sun sets, the migrators start swimming. Imagine it like a huge stadium wave across the world's water bodies.

WHAT IS NEXT?

Scientists are continually generating new ideas about what controls the timing, depths, and duration of DVM. Evidence now suggests that DVM may not be as simple as a direct response to light. In fact, the temperature and oxygen levels of the water, and even the genetic make-up of individual animals, are other factors that determine where animals are positioned in the water column over the daily cycle [2].

As the oceans continue to warm with climate change, scientists also want to understand how changing environments will affect DVM. For example, fish and zooplankton are moving north to stay within their optimal temperature ranges. This may bring them in to new light conditions, exposing them to longer days in summer and shorter days in winter [5]. How might this new light environment affect their migrations? Will they adapt their finely tuned strategy, or will populations experience lower rates of survival?

Scientists are interested in these questions because zooplankton and their DVM are of huge importance. This is because, after feeding all night at the surface, the zooplankton migrate to depths, taking their carbon-filled poo with them. These poo pellets act as speedy vehicles for carbon, which can be locked up for thousands of years when it reaches the bottom of the sea [6]. As the levels of carbon in our atmosphere are contributing to global heating, any changes to zooplankton populations could have big consequences for the efficiency of this carbon removal and for the ocean's ability to help regulate global climate.

Overall, the phrase "better to be hungry than dead" [7] neatly summarizes the reason why so many animals undergo the gargantuan game of hide-and-seek known as DVM. By feeding at night and hiding during the day, DVM allows them to balance their need to eat with avoiding to be eaten! DVM is essential for understanding these mighty migrators and their many roles in the open ocean. You might say it is game-changing.

ACKNOWLEDGMENTS

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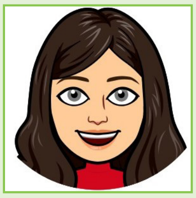
YOUNG REVIEWER



GEMMA, AGE: 16
My name is Gemma, I am 16 years old and I love playing sports and music.

AUTHORS

JENNIFER J. FREER
I am a marine scientist at the British Antarctic Survey and have always been fascinated by life in the oceans. My work aims to help understand how marine animals are distributed, what controls their distributions, and how climate change might affect them. I study zooplankton and pelagic fishes found in the polar oceans and use model-based tools to predict their future ranges. Whether it is spending time on a ship, beach walks, or surfing, I am happiest on or by the sea. *jenfree@bas.ac.uk

LAURA HOBBS
I have always considered myself a thalassophile—a lover of the oceans. For the past 10 years or so, I have spent as much time as possible working in the Arctic. I find it an absolutely fascinating place to study. The light cycle is completely unique, and the midnight sun and the polar night present really interesting questions in ecology, particularly with respect to animals that respond to light (such as zooplankton). I use lots of different methods to study zooplankton, and some of this involves installing instruments in the Arctic Ocean for a year at a time.

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FOR YOUNG MINDS

THE EARTH AND ITS RESOURCES
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MARINE COPEPODS, THE WILDEBEEST OF THE OCEAN

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YOUNG REVIEWER:

LEONARDO
AGE: 14

Copepods are amongst the most abundant animals on our planet. Who knew?! These small (typically 1–10 mm) crustaceans are found in all of the world's oceans and play an important role in regulating Earth's climate. Like wildebeest in the Serengeti graze on grasslands and are food for lions, herbivorous copepods represent a vital link in oceanic food chains between microscopic algae and higher predators, such as fish, birds, and whales. A group of copepods called *Calanus* are particularly important in the Northern Hemisphere. These tiny-but-mighty animals also share the wildebeest's need to make a large annual migration—but in their case, they sink thousands of meters downwards to spend the winter in the deep, dark ocean. Understanding the lives of marine copepods, and how their

populations will respond to climate change, is crucial for predicting the future health of the marine environment and how it helps our planet.

CALANUS THE COPEPOD

Copepods are tiny crustaceans—distant relatives of crabs and lobsters. They are members of the zooplankton, animals that drift at the mercy of ocean currents. Their name is derived from the Greek words "cope" and "podos," literally "oar-foot," reflecting their large limbs that propel them through the water. At any moment, there are billions of copepods swimming around in all of the world's oceans.

One of the most important groups of copepods in the Northern Hemisphere is called *Calanus* (Figure 1). A single adult *Calanus* may only measure a few millimeters in length, but the total existing population of *Calanus* probably weighs more than all of the 7.7 billion people currently alive on Earth. The huge abundance of *Calanus* is what makes them so important for the healthy functioning of marine ecosystems.

Just as wildebeest are the main grazers of the Serengeti, so *Calanus* are the great grazers of the Atlantic and Arctic oceans, feeding on aquatic meadows of phytoplankton, microscopic plant-like algae that bloom in spring. *Calanus* filter the chlorophyll-rich phytoplankton out of seawater using rapid movements of their feathery mouthparts and their sense of touch (Figure 1).

The bodies of *Calanus* are transparent, which may explain why the famous eighteenth century Norwegian bishop and scientist Johan Ernst Gunnerus named them after the philosopher Kalanos (Calanus), who refused to wear clothes! For an apparently "simple" animal, *Calanus* has a complicated life cycle (Figure 2). The cycle begins in spring when adult females release batches of 50 or more eggs into the water. The eggs hatch a day or so later and, being cold-blooded, develop at a rate that is largely controlled by water temperature. Like all crustaceans, *Calanus* has a rigid external skeleton (exoskeleton) that it must shed in order to grow and develop. In total, there are 12 development stages to their life cycle. During the first 6 they are known as nauplii. These "baby" stages adopt a swimming-by-jumping approach to movement and look like tiny pulsating hands. The 6 later stages are known as copepodites, all of which have the cylindrical shape that is characteristic of *Calanus* (Figure 1). In the laboratory, it takes between 30 and 80 days for an egg to develop into an adult, depending on the water temperature and feeding conditions. In nature, however, this process is often interrupted by spending winter at great depths as an immature adult (Figure 2).

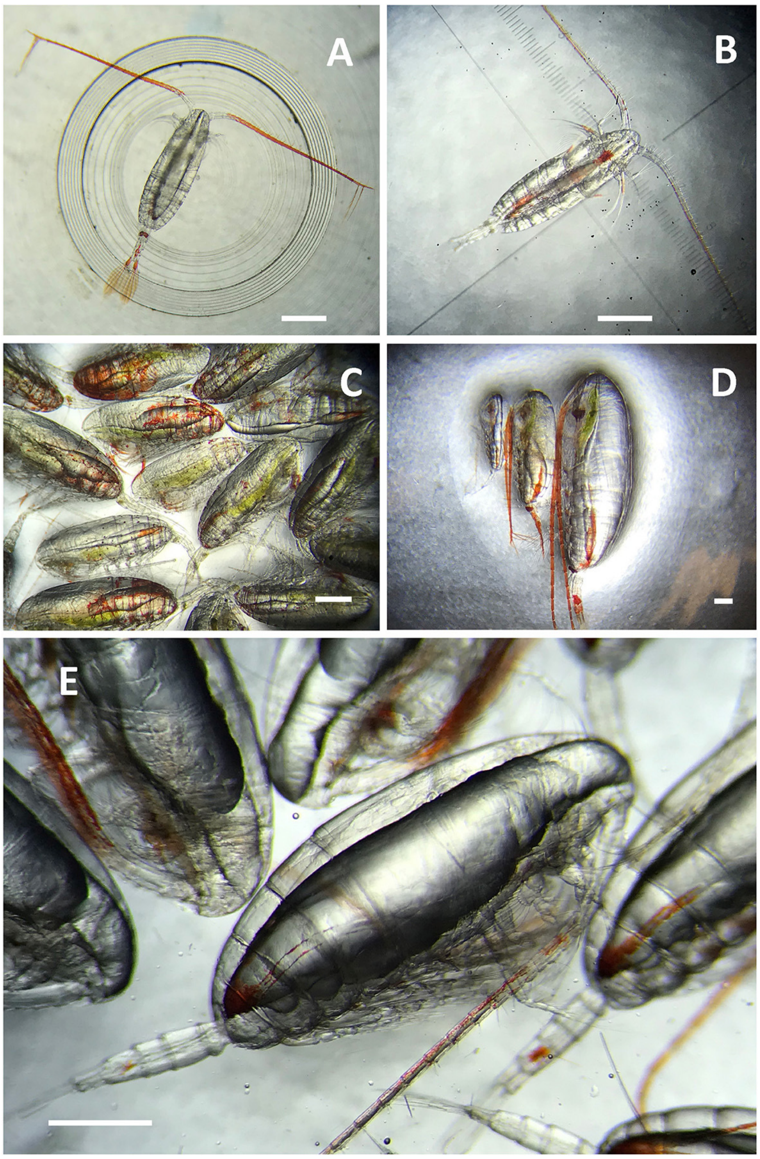

Figure 1

Figure 1

(A,B) The marine copepod, *Calanus*, has broad, sensory antennae and feathery tail-like structures that help them detect and evade predators. **(C)** Their green phytoplankton-packed guts are clearly visible through their transparent bodies. **(D)** Three closely related species of *Calanus* live together in the Arctic Ocean: *Calanus finmarchicus* female (left), *Calanus glacialis* female (middle), and *Calanus hyperboreus* female (right). **(E)** The body cavities of "hibernating" *Calanus* are packed full of fat to fuel them through the winter months without feeding. Horizontal scale bars represent ~1 mm. All images copyright Daniel Mayor (NOC).

ADAPTATIONS TO LIFE IN THE OPEN OCEAN

Two of life's main challenges are (1) finding enough food, and (2) avoiding being eaten while doing so. Facing these challenges helps an animal to live long enough to reproduce. *Calanus* is so successful because of their response to these two challenges.

Calanus congregate to feed on dense patches of phytoplankton near the ocean's surface. Coming together in groups is dangerous—there is nothing to hide behind to avoid being seen by predators—so being transparent helps. But *Calanus* do not need light to feed, so they reduce their risk of becoming fish food by feeding under the cover of darkness. At sunrise, *Calanus* descend to hide in the deeper, darker depths. This dilutes their population into the vastness of the deep

Figure 2

The life cycle of *Calanus finmarchicus* spend the "active" component of their life in the upper ocean, where they grow through 12 developmental stages (6 as nauplii, and 6 as copepodites) of increasing complexity. At the end of summer, immature adult animals (copepodite stage 5) migrate into deep water and enter the dormant component of their life cycle called "diapause." This is similar to hibernation in mammals and other land animals. In early spring, these "sleeping" animals wake up, develop into adults (copepodite stage 6) and migrate back to the surface to reproduce. Image copyright Holly Jenkins (NOC).

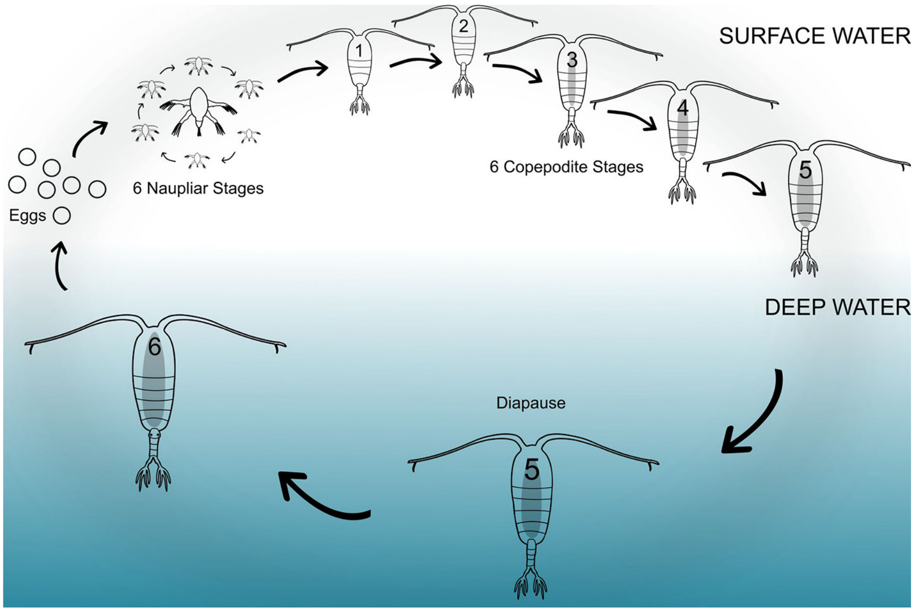

Figure 2

ocean and makes the job of a predator a bit like hunting for a needle in a haystack while also wearing a blindfold. When daylight fades, the migration is reversed and *Calanus* move back to the surface to feed again.

The dense phytoplankton blooms of spring and early summer provide excellent feeding conditions for *Calanus*. Just like animals on land, this spring bounty allows *Calanus* to prepare for the long, dark winter months by storing fat. So much so that their bodies become swollen by their blubbery-burden (Figure 1). As the summer fades to autumn, the phytoplankton that once fuelled *Calanus* all but disappear and the upper ocean becomes a food desert. This triggers one of the greatest migrations on Earth.

The population of immature *Calanus* sinks down into the ocean's interior, as deep as 2 km in some places, where it spends the winter in a dormant state called diapause for up to 9 months (Figure 2). Diapause is similar to hibernation in mammals, such as polar bears, when the animals rely entirely on internal fat reserves. The near-freezing temperature of the deep ocean slows down the rate at which *Calanus* use up their stored fat reserves, and the perpetual darkness keeps them safe from hungry eyes.

When spring arrives, the dormant population of *Calanus* awakens and begins its ascent toward the surface. Only now do the animals become adult males and females in anticipation of the next mass feeding and reproductive cycle. *Calanus* is certainly not the only copepod to overwinter in the deep sea using internal fat stores to survive—but it is by far the most abundant one to do so in the North Atlantic and Arctic oceans.

THE IMPORTANCE OF *CALANUS*

Spring blooms of phytoplankton transform the North Atlantic and Arctic Oceans into a *Calanus*-rich soup. Unfortunately for *Calanus*, their large numbers do not go unnoticed. Countless marine organisms are dependent upon *Calanus* as a food source. These range from microscopic parasites that live inside their guts, to the bowhead whales that individually consume an estimated 100 tons of *Calanus* and other crustaceans each year (that is the same as eating 760 wildebeest!). Many species of fish, birds and whales travel huge distances to feed upon the *Calanus* population explosion that follows the spring phytoplankton bloom.

From a human perspective, the most important relationship is between *Calanus* and fish. *Calanus* are the preferred prey of many fish, so when there are a lot of *Calanus*, there are a lot of fish. And this is good news for the many people who make their livings and feed their families by catching fish, such as cod, herring, capelin, and mackerel.

Calanus also play an important role in helping the oceans regulate the Earth's climate. Phytoplankton grow by transforming carbon dioxide (CO_2) into living matter via photosynthesis. This process removes hundreds of millions of tons of CO_2 from the atmosphere every year. Transformed into phytoplankton, this CO_2 becomes *Calanus* food and, like all animals, some of what gets eaten by *Calanus* comes out of their rear ends. *Calanus* produce dense, torpedo-shaped droppings. These droppings transport carbon downwards into the deep ocean, trapping it away from the atmosphere for hundreds or thousands of years. This process helps slow the rate of global warming. During periods of peak *Calanus* abundance, most of the particles raining down into the ocean's abyss are in the form of these climate change-busting torpedoes. Daily vertical migrations help speed up this process as *Calanus* drop their "bombs" at depth during daylight hours. These vertical migrations into the deep sea further contribute to removing carbon from the atmosphere. In the ocean depths, *Calanus* slowly burn off their carbon-rich fat reserves and "breathe out" CO_2 into the water. This CO_2 would not come back into contact with the atmosphere again for thousands of years.

CLIMATE CHANGE EFFECTS ON *CALANUS*

The ever-rising concentration of CO_2 in our atmosphere is causing a progressive warming of our climate and thus the ocean. This warming is having profound effects on ocean life. Over the last 5 decades, there has been a progressive northward shift in the habitat ranges of *Calanus* as temperatures there become more favorable to them. Exactly how this redistribution of the *Calanus* species will affect ocean ecosystems remains unknown.

Ocean warming is also causing a potential mismatch between *Calanus* and their food. Long-term records show that ocean warming is causing cold-blooded zooplankton, including *Calanus*, to reach their highest numbers earlier and earlier each year. At first glance this sounds good—the animals develop faster, get fat quicker, and go into diapause sooner (thus avoiding being eaten). The phytoplankton blooms that *Calanus* depend upon, however, do not show the same response to ocean warming. So, as the years advance, the timing mismatch between *Calanus* and their food is becoming progressively greater. This has potentially important consequences for the future success of *Calanus* and the many vital roles they play in the ocean. A major goal of on-going marine research is to understand how *Calanus* will respond to further climate change, and how these responses will impact the ocean's ability to regulate global climate and produce harvestable resources, such as fish.

DNA FINGERPRINTING *CALANUS* SPECIES

There are several related species of *Calanus* that can be found in huge numbers from the Mediterranean Sea (*Calanus helgolandicus*), up through the Atlantic Ocean (*Calanus helgolandicus*, *Calanus finmarchicus*), and into the Arctic Ocean (*Calanus finmarchicus*, *Calanus glacialis*, *Calanus hyperboreus*) (Figure 1). Being able to identify each species accurately is crucial for us to understand if and how their populations are changing.

The different species of *Calanus* can be quite difficult to tell apart from each other. Often, the only thing telling one species from another is the subtle difference in the shape of the inside of their legs! Thankfully, modern genetic "fingerprinting" tools can now be used to identify the various species of *Calanus*. The process of genetically fingerprinting *Calanus* begins by researchers making many copies of the organism's DNA. This DNA is then cut up into smaller pieces with DNA scissors, called restriction enzymes, which recognize and cut the DNA in very specific places. The sequence of DNA varies between the species, meaning that the DNA is cut in different places for each species. Differences in the resulting DNA strand sizes after cutting can be seen when the pieces are separated using a technique called gel electrophoresis. This technique produces a unique pattern for each species. Just like each item in the supermarket has a unique barcode to identify it at the checkout, we can use the pattern of DNA pieces to identify the species of *Calanus* (Figure 3).

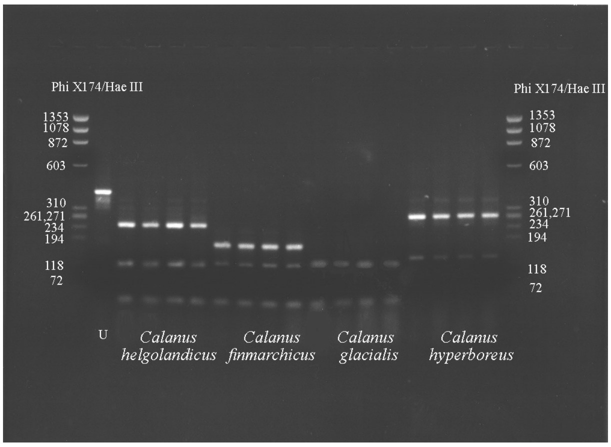

Figure 3

Figure 3

Genetic fingerprinting of four *Calanus* sibling species; *Calanus helgolandicus*, *Calanus finmarchicus*, *Calanus glacialis*, and *Calanus hyperboreus*. For each species there is a different pattern or "fingerprint". This is because when the DNA is cut up it results in pieces of different sizes. The smaller pieces of DNA run further down the gel than the bigger pieces, resulting in a pattern unique to each species. The pattern is seen as the light bands in each column (four columns for each species), the column labeled U is "undigested," DNA that has not been cut up by the DNA scissors or restriction enzymes. The columns on the outside left and right are DNA markers, bands of DNA of known size that we can use to compare the sizes of our cut-up DNA. For example the undigested DNA is between the 310 and 603 bands of the DNA marker, which indicates the DNA is just over 400 base pairs in size when it has not been cut. Image copyright Pennie Lindeque (PML).

FUTURE OUTLOOK

Calanus research over the past century has helped us understand and appreciate the importance of these animals for global climate regulation and as a source of food for countless other marine organisms. However, with every new discovery comes the realization that we still have so much to learn. For example, how do these animals decide when to go into and come out of hibernation? And how will future changes in their diet affect their ability to fatten up for winter or produce healthy offspring? Perhaps you will become part of the next generation of plankton biologists that helps answer these and other fundamental questions about *Calanus*?

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

LEONARDO, AGE: 14

I am Leonardo, I am in high school now and I really like math and science, I do not really like writing or reading. I hope to become a mathematician. In my free time I mainly play piano and videogames.

AUTHORS

DANIEL J. MAYOR

I am a Biological Oceanographer, and lead the Pelagic (open-ocean) Ecosystems sub-group at the National Oceanography Centre, UK. My research examines how zooplankton are affected by climate change, and the consequences for the global carbon cycle and climate regulation. Spending time at sea allows me to indulge three of my passions; plankton, traveling, and reggae music (much to the bemusement of my wife and kids)! I really enjoy making things, and am half way through building my own house. See more wonderful plankton on Instagram (oceanplankton). *dan.mayor@noc.ac.uk

KATHRYN B. COOK

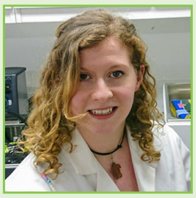
I am a Pelagic Biogeochemist at the National Oceanography Centre, investigating how the abundance and structure of marine zooplankton communities relate to the functioning of the ecosystems within which they reside. I studied marine biology at the University of Plymouth, and discovered my love of zooplankton whilst working as a zooplankton analyst at the Plymouth Marine Laboratory. After completing my Ph.D. in zooplankton ecology at University of Wales, Swansea, I worked at Marine Scotland Science (MSS) in Aberdeen as a plankton biologist.

THOMAS R. ANDERSON

I am a senior researcher at the National Oceanography Centre, Southampton. I make computer models to study the role of ocean plankton in the global carbon cycle and climate change. It is interesting work because, like plants and animals on land, there are many different types of plankton. Understanding this diversity, and how plankton live together in ecosystems, is the key to making successful model predictions. The models run on supercomputers that track the plankton as they circulate in the world ocean. When I am not working, I enjoy watching sport on TV, despite the groaning from my wife!

ANNA BELCHER

I am a marine scientist at the British Antarctic Survey in Cambridge, UK. I am really interested in how ocean biology is involved in the global carbon cycle and getting carbon dioxide out of the atmosphere. In particular, I study Antarctic krill, fish living in the dark ocean, as well as the importance of the food that copepods eat for their overwintering at depth. When I am not in the office or out at sea collecting data, I spend my time rock climbing, bike-packing, and enjoying the wild outdoors.



HOLLY JENKINS

I am a Ph.D. student at the National Oceanography Centre, UK. My background is marine biology, and I am interested in both the effects of climate change on marine animals and the way the animals affect climate change. My research looks at the diet of copepods to see what is needed for growth and reproduction. This is important to understand so we can anticipate how copepods will be affected by future climate change. I find copepods fascinating as they appear simple at first glance, but actually have complex daily movements, life cycles, and needs.

PENNIE LINDEQUE

I am a marine biologist at the Plymouth Marine Laboratory. My work focuses on zooplankton, small animals at the base of the marine food web. I develop and use molecular techniques to identify zooplankton, investigate what they eat and what eats them, and to look at their response to environmental stress and pollution. I am also interested in the source, distribution, and impact of microplastics and microdebris as marine contaminants on marine animals, including zooplankton.

GERAINT A. TARLING

I am a biological oceanographer at the British Antarctic survey. I work at both poles, surveying the range of animals inhabiting the sunlit and twilight oceanic zones. These organisms range from microscopic zooplankton to deep-dwelling fish, also encompassing gelatinous organisms, krill and pteropods (sea-butterflies). I am particularly interested in how they behave, most notably their daily migrations from ocean depths to the sea surface. I am also interested in how much carbon these communities move from the upper to the deeper parts of the ocean and how effective this process is in compensating for human emissions of CO_2. When on long, polar voyages, I pass my spare time playing the accordion and spotting wildlife.

DAVID POND

I am based at the University of Stirling, studying how marine organisms utilize fats to succeed in life. I work at the interface between biochemistry and ecology, investigating how the biochemical composition of fat influences animal metabolism and health. My current work examines how marine copepods regulate their buoyancy and control key stages of their lives by changing the composition of fats within their bodies. This involves the use of an instrument that allows me to see how different fats change between being a solid and a liquid across the temperature and pressure gradients observed in our oceans.

THE EARTH AND ITS RESOURCES
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LIFE INSIDE AND UNDER FROZEN SEAWATER

***David N. Thomas*[1*] and *Hermanni Kaartokallio*[2]**

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[2] *Finnish Environment Institute (SYKE), Marine Research Centre, Helsinki, Finland*

YOUNG REVIEWERS:

PRICE
AGE: 12

PRINCESS
AGE: 14

PROVIDENCE
AGE: 8

Seawater freezes below −2.0°C and therefore ice covers vast areas of the polar oceans for part of every year. First, ice crystals float to surface; then ice floes form to create a frozen landscape on the ocean surface. This pack ice moves with wind and currents and can form huge piles of ice rubble or expose open water when ice floes move apart. When seawater freezes, salty brines are trapped in a network of tiny channels and pockets throughout the ice. This network is a living place for microscopic ice organisms like bacteria, algae, tiny animals, small worms, and crustaceans. Ice algae grow best on the underside of ice where animals can feed on them. Sea ice is an important site of food production for many organisms in the polar oceans and seas and when the ice melts, it can also support life on the sea floor, which can be thousands of meters below.

SEA ICE FORMATION

Freshwater from a lake, river, bird bath, or tap freezes at 0°C. If salt is added to water, the freezing point goes down. This means that

Figure 1

Figure 1

When ice begins to form, vast areas of what is called grease ice form slicks on the ocean surface.

seawater, which generally has a **salinity** (salt content) of 30–35 g of salt per liter, does not start to freeze until around −2.0°C.

SALINITY

The salt content of water is called salinity—water with no salt has a salinity of 0, seawater with 35 g of salt per liter has a salinity of 35 and salty brines with 200.

In the polar regions during autumn (August/September in the Arctic, March/April in the Antarctic), rapidly falling air temperatures cool the surface waters below the freezing point. Surface layers of the oceans, up to several hundred meters below the surface, are constantly being mixed by wind and water motion. When the freezing starts, tiny ice crystals begin to appear everywhere in the surface water layer and float to the surface. This is the beginning of what is called **pack ice**: the frozen realms that have captured the imagination of explorers and adventurers for hundreds of years [1].

PACK ICE

Sea ice that is moved around by ocean currents and wind.

As more and more ice crystals accumulate on the surface of the water, they form a layer with the consistency of a thin porridge. The "porridge-ice" is then moved around by wind to form huge slicks of ice crystals that can cover many km^2 (Figure 1). On the surface, the ice is in contact with the cold air and the crystals freeze together to form a more rigid ice layer. When the cold seeps through the ice, the ice grows mainly from bottom and freezes the seawater that is in contact with the bottom of the ice layer. Within a few weeks, the ice can be more than 1 m thick.

The ocean waters are constantly moving, and ice is broken into large pieces called **ice floes**, which float on the ocean surface. Ice floes can range from a few meters to over 100 m wide. Many floes can freeze together to form continuous ice floes up to several kilometers wide. These in turn can then break up again into smaller floes as the ice moves with currents, tides, and wind. When wind and currents force ice floes against each other, they can pile on top of each other and form huge ice piles called ridges (Figure 2B). Also, the wind can pull ice floes apart to expose open stretches of water called leads. The constantly moving ice creates a landscape (or a frozen-scape) that changes day by day and even hour by hour (Figures 2A,B).

ICE FLOE

A continuous area of sea ice. These can vary in area from a few m^2 through to floes several km^2.

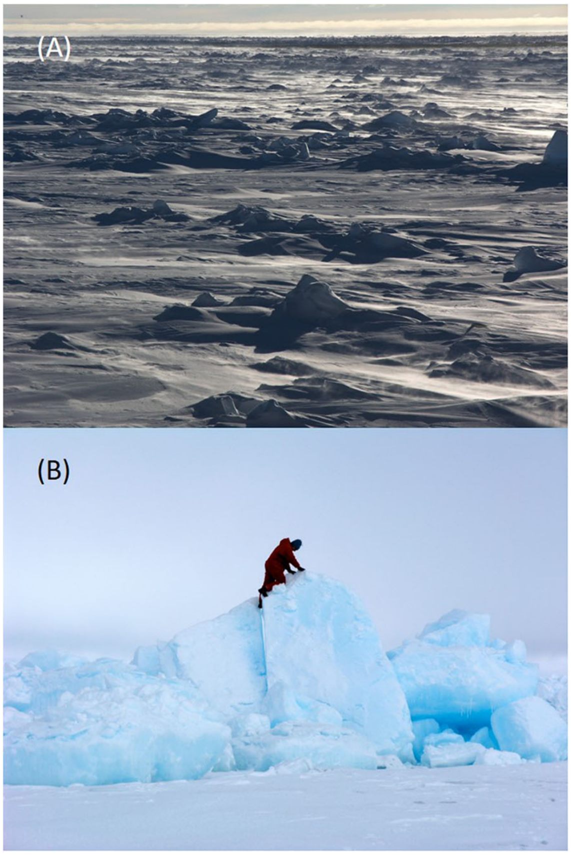

Figure 2

Figure 2

The pack ice of the Arctic and Antarctic Oceans is a varied environment that can be quite hostile to life. **(A)** Cold windswept landscapes which from the surface seem devoid of life. **(B)** Big slabs of ice pushed into the air to form ridges as ice floes colide.

INSIDE SEA ICE

Growing ice crystals are pure water and do not contain any salts or other compounds that are normally dissolved in the seawater. Therefore, as the ice crystals freeze together to form more solid ice, all the dissolved substances in the seawater are forced out, creating a very salty liquid called a **brine**. This brine collects in a network of very small channels, called **brine channels**, and small holes called **pores** within the growing ice. The best comparison is to think of Swiss cheese or a sponge, where the solids are ice and the holes are filled with a salty brine.

BRINE

A solution with high concentrations of salt.

As ice gets colder, the size of the brine channels and pores gets smaller and the salinity of the brines within them increases. The ice at the bottom of an ice floe will be at the freezing point of seawater (around −2°C) and the ice at the top of the floe will be close to the air temperature. As air temperatures during polar winters can be as low as −30°C, there will be a temperature gradient between the top of the ice near the air and the bottom of the ice. Because of this gradient, the colder ice at the top of an ice floe will have smaller brine channels and pores filled with higher salinity brines than those that are found lower in the ice.

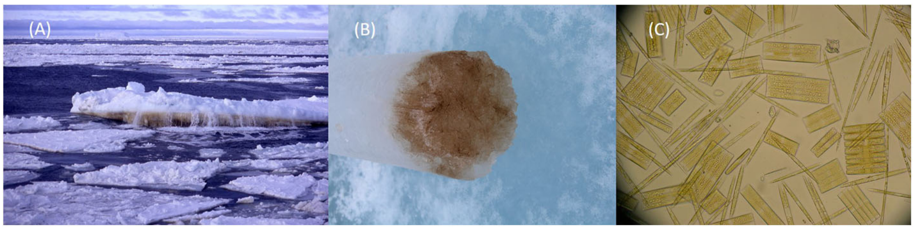

Figure 3

Figure 3

(A) Rich accumulations of living things stain the underside of ice floes brown. **(B)** Brown ice sample taken with 10 cm diameter ice-corer. **(C)** Microscope image of sea-ice diatoms, magnified about 1,000× (image J. Stefels).

LIVING IN THE ICE

In autumn, as the ice crystals float upwards through the water, they catch particles between themselves, collecting the particles into the ice porridge that is forming on the ocean surface. All kinds of small things floating in the water can be caught by the ice crystals. These can be micro-plastics or sediments, as well as living microscopic creatures like bacteria, microalgae, larvae, and small crustaceans. Basically, anything that sticks into the ice crystals and cannot swim away can be moved from the open water into the ice.

Organisms that can live in the ice must be able to survive freezing temperatures, but they also must cope with high and ever-changing brine salinities. Most importantly, they need to be small enough to avoid getting stuck and frozen within the small brine channels. This is not such a problem at temperatures warmer than −10°C, but at colder ice temperatures, around −20°C, the spaces between ice crystals are so small that there is space for only the smallest of bacteria [2].

At the bottom of ice floes close to the seawater, the ice can be packed with organisms. In fact, there is so much life that sometimes the ice is colored yellow or a rich coffee color (Figures 3A,B). The most common creatures in the ice bottom are tiny algae. There are also many bacteria that live in the slimes produced by ice algae and the remains of dead organisms. A group of algae called **diatoms** are the most common group of ice algae (Figure 3C). Diatoms grow inside hard shells that look like tiny, ornately patterned boxes made of silicate, which is like a tough glass.

DIATOMS

Unicellular algae common in seawater and freshwaters. They are characterized by being encased in tough outer covering made of silicate (like glass).

Algae, like plants, use photosynthesis to capture light energy to grow. It is quite dark at the bottom of an ice floe, especially if it is covered in a layer of snow. Therefore, those algae that grow well in sea ice are good at growing in low light. To do this, they must have more of the chemical pigments needed to trap the light that fuels photosynthesis. It is the high amount of these light-trapping pigments that results in the color of the ice.

To survive the low temperatures and high salinities in the brines, the algae must adjust their internal environment to balance the changes in the external environment, by increasing or decreasing some chemicals within their cells. Some of these chemicals can regulate the pressure inside the algal cells, so they do not shrink or explode from differences in salinity. Other chemicals can also act as anti-freeze agents. Many of the algae and bacteria that thrive in the ice cover the outside of their cells with gel-like coatings. These coatings protect the cells from ice crystal damage and the most drastic changes in temperature and salinity.

SEA-ICE ALGAE CAN PROVIDE FOOD FOR MANY ORGANISMS

The high numbers of algae and bacteria in ice create rich feeding grounds for other organisms that eat them. Crustacean copepods are small shrimp-like creatures that can be found in high numbers in the lower, "warmer" layers of the ice, where they eat ice algae and bacteria. In colder parts of the ice where brine channels are smaller, more flexible-bodied animals, such as flat worms called turbellarians, round worms called nematodes, and simple organisms called ciliates can live in high numbers. These animals can shrink in high salinity water and swell in lower salinity water, which helps them move through the brine channel system.

The lower layers of an ice floe are generally where most of the living things can be found (Figure 3A). This in turn draws larger organisms to the underside of the ice, where they can feed on organisms growing between large ice crystals hanging from the bottom of the ice, like a bright brown, upside-down meadow glowing from the light above. Such organisms are many and varied, including sea slugs (nudibranchs), larger crustaceans, such as krill and even fish. The ice is a very important source of food for these larger animals, especially in winter when there is little to no food in the dark waters below. The small algae-eating animals under the sea ice are in turn food for even larger animals, such as seals, penguins, and other marine birds. Sea-ice algae growth is therefore very important for much of the life in pack ice-covered waters.

Sea-ice algae can entirely cover the undersides of ice floes in spring and early summer (Figure 3). Some species even form strands and clumps hanging from the underside of the ice. Sooner or later, if not eaten, this rich food supply drops from the ice and sinks into the water. It can even reach the deep-sea floor thousands of meters below the ocean surface. On the seafloor, it is food for large, mobile animals like sea cucumbers and brittle stars [3].

SEA-ICE ECOSYSTEMS ARE VULNERABLE

Although sea ice is an important living space for organisms in winter, it is only a short-lived one. In spring and early summer, as air and water temperatures increase, the ice starts to melt. This releases all the organisms living inside it back into the water, where they stay until the next cycle of freezing starts the next autumn. Even though the sea ice comes and goes, the huge areas covered by sea ice in the autumn and winter (Arctic 15 million km^2 and Antarctic 22 million km^2) make it one of the largest biomes on the planet. The area covered by sea ice on Earth is as large as the area covered by savannahs or crop lands. In both the Arctic and the Antarctic, we are already seeing that the changing climate is greatly altering the timing of when sea ice forms and melts, as well as the nature of that ice. Recognizing the importance of the life that thrives in and on the ice is critical for our understanding of what these climate changes will mean for entire ecosystems that are associated with sea ice.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

PRICE, AGE: 12

Price loves making up stories and has also written a book (Ms. Wasteson and the waste empire). She enjoys gymnastics, athletics, volleyball, and basketball. She is brave and bouncy. Price also enjoys quality time with family and is very creative. At her school, she is part of a "green team" that works to protect the environment. She likes debating and has a passion to study and become an activist against social injustices.

PRINCESS, AGE: 14

Princess has many ideas and goals and is passionate about helping others to be better. She is a deep thinker while solving problems. Princess is funny, sporty, jumpy, and a kind person, who loves exploring to find solutions. She is creative, narrative, and likes writing. Princess wrote a book titled "Sarah and the waste center." She loves learning new things. She is into volleyball, music, band, art, and digital photography. Her purpose is to learn more about science, and to improve her writing and editing skills.

PROVIDENCE, AGE: 8

Providence is the youngest amongst her three sisters. She is playful and bouncy. Providence is curious, talkative, and likes asking many funny questions, that leaves others laughing. She loves making new friends and traveling. Providence loves science experiments. During this process, she may destroy, repair or recycle some household items. As part of this adventure, Providence repaired a spoilt speaker. But after weeks of action, she modeled the speaker wires into skipping ropes. She is passionate over music and sports.

AUTHORS

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David N. Thomas is a Professor of Marine Biology at Bangor University, U.K. His research spans a wide range of subjects around the ecology and physiology of marine seaweeds and phytoplankton. His work is very much at the interface of biology and chemistry in marine, estuarine, and river systems. He has extensive experience studying the life that lives within, on, and below frozen pack ice in the Antarctic and Arctic Oceans and Baltic Sea. *d.thomas@bangor.ac.uk; david.thomas@helsinki.fi

HERMANNI KAARTOKALLIO

Hermanni Kaartokallio is a Senior Research Scientist at the Finnish Environment Institute (SYKE) Marine Research Centre, Helsinki, Finland. His research is focused on marine bacteria, especially in sea ice and other cold environments in the Baltic Sea and Arctic. This includes bacterial activity, production, processes, communities, and interactions with their environment. He studies bacteria in waters as they pass from land through rivers to coastal waters and how bacteria survive in cold marine environments.

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FREEZING IN THE SUN

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YOUNG REVIEWERS:

ECOLE PRIMAIRE PAUL BAUDRIN

AGE: 10

When the air is very cold, water at the surface of the ocean freezes, forming sea ice. Parts of the Arctic Ocean are covered by sea ice during the entire year. Often, snow falls onto the sea ice. Despite the cold, many plants and animals can live in the Arctic Ocean, some in the water, and some even in the sea ice. Particularly, algae can live in small bubbles in the sea ice. Like other plants, algae need energy to grow. This energy comes from food and sunlight. But how can the sunlight reach these little algae living inside the sea ice? From the sun, the light must pass through the atmosphere, the snow, and finally the sea ice itself. In this article, we describe how ice algae can live in this special environment and we explain what influences how much light reaches the algae to make them grow.

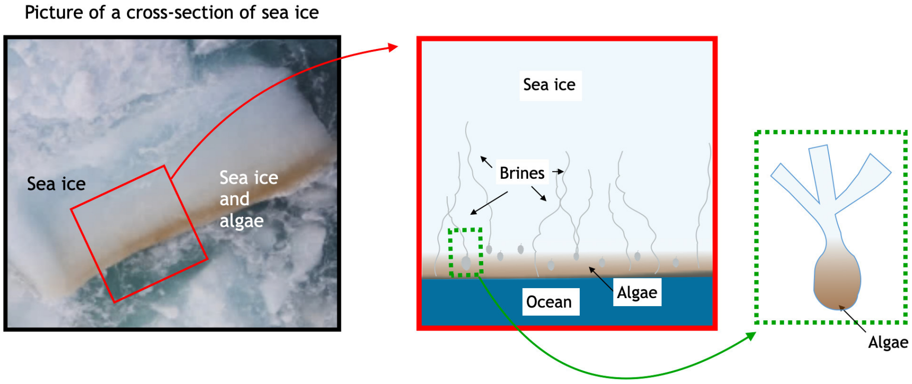

Figure 1

Figure 1

The left panel shows a picture of a sea ice block, turned horizontally. A brownish layer of algae is visible at the bottom. The middle panel shows the small bubbles, connected by veins, that make up the brine pockets that the algae live in. The right panel shows one pocket full of algae, which create a greenish-brown color.

SEA ICE: THE HOUSE OF ALGAE

If you think about an ice cube, like the ones in a cold drink in summer, you can hardly believe that something could live inside it. But the **sea ice**, which is ice formed from freezing sea water, can indeed be the home for little organisms. How is this possible, and where do these organisms live? Ocean water contains both salt and algae. When the water freezes, some of these salt grains, and some algae, remain trapped in the ice. The salt grains melt some of the ice around them and create little bubbles filled with salty water [1]. These bubbles are called **brine pockets**. The brine pockets can be up to 5 mm in size, the diameter of a pencil, and they grow larger during the spring and summer seasons. Since algae are smaller than 1 mm, they can comfortably live inside the brine pockets (Figure 1). As the sea ice grows thicker, the brine pockets are pushed toward the bottom of the sea ice. Thus, algae live mainly in the bottom layer of the sea ice (Figure 1).

SEA ICE

Frozen ocean water.

BRINE POCKETS

Small bubbles of salty water inside the sea ice.

HOW BIG IS ALGAE'S HOUSE?

An ice cube in your drink is relatively small; you can easily take it in your hand. But how big is sea ice? Sea ice covers large parts of the Arctic Ocean. It starts to form in autumn, when the air gets increasingly colder, and it reaches its maximum extent in late winter (February to March). The sea ice starts to decrease its extent again in late spring when the sun warms up the atmosphere and the surface of the ice, causing the ice to melt. We can imagine sea ice as a large blanket covering the Arctic Ocean. This blanket gets larger when it is cold and shrinks again when it is warmer. The sea ice also becomes thicker in winter and thinner again in summer. Sometimes the ice wrinkles and it can also break into pieces of varying sizes, from small pieces with a diameter of just a few meters up to large pieces of several kilometers. In winter the ice is the thickest, the blanket is the largest, and the most wrinkles are present.

The extent of sea ice in winter can reach 14 million km^2, an area of about 2 billion football fields, and it can easily be 2 m thick, same as the height of a basketball player. When it crumples, the ice can create wrinkles that are 3 or 4 m high above the water and that reach down 10–15 m into the water. Moreover, in winter, snow accumulates on top of the sea ice. The snow is usually 20–30 cm thick. If you imagine the Arctic sea ice as a house inhabited by algae, the algae would live in the basement, at the bottom of the sea ice, often covered by a "roof" of snow.

ALGAE NEED TO EAT... AND TO BE EATEN

Having a house, of course, is not all that algae need to live; they also need food. Algae are plants, so they need sunlight and carbon to perform **photosynthesis** [2], to create the energy they need to grow. Carbon is usually contained in sea water, so each brine pocket has a bit of carbon that can be used by the algae. What about sunlight? In the Arctic during the summer, days become so long that there is no night for about 2 months. On the other hand, in winter, the nights are so long that there is no light at all. Thus, algae can grow only in summer, when there is sunlight, and they die in winter, when it is dark. Dead algae are broken down and their nutrients are recycled, the same way plants that grown on land are. Algae are important because they are food for animals. As on land, the ocean is populated by small animals that eat plants. These animals are similar to shrimps or insects, but very small. The animals that eat plants are then eaten by bigger animals, like fish. Fish are eaten by birds and seals, which are then eaten by the biggest predator in the Arctic: the polar bear. Thus, sea-ice algae are important in the Polar regions because they are the first link in the Arctic marine food chain.

PHOTOSYNTHESIS

A process by which plants use sunlight to produce food and energy.

A LONG WAY FROM THE SUN TO THE EARTH

The light that we receive every day on the Earth originates from the Sun, our very own star. This light, which is sent permanently by the Sun in the form of rays, has to make a long journey through the solar system to reach the Earth. Once the sun rays reach our planet, they still need to get through the atmosphere before they can provide us with energy and warm us up. The atmosphere is the huge layer of air around the Earth's surface that allows us to breathe. It is composed of a lot of tiny **molecules** of different gases. When the sun's rays cross the atmosphere, some of them are reflected back into space by the gas molecules and also by the little water droplets that form the clouds (Figure 2). Other rays are absorbed by the particles. So, only a little more than half of the sun's rays (∼55%) will reach the Earth's surface [3].

MOLECULES

Very small particles that are the material from which every solid, liquid, or gaseous material is made.

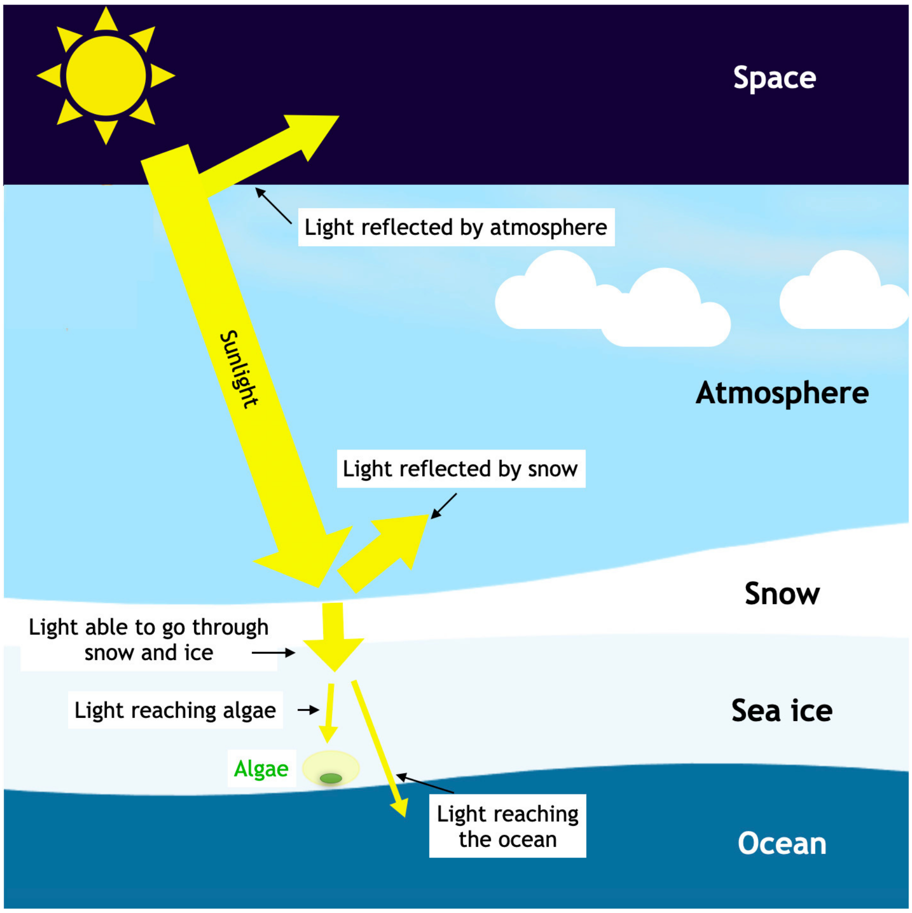

Figure 2

Figure 2

Light has a long and difficult journey from the sun to the sea-ice algae. The yellow arrows represent the sunlight. The width of the arrows represents the amount of light: the thinner the arrow, the less sunlight available. Some of the sun's rays are reflected back into the atmosphere by the snow layer, and some of the rays are absorbed by the snow and the ice. The amount of light that reaches the algae is very small compared to the amount of light that originally hit the snow.

THE DIFFICULT JOURNEY OF SUNLIGHT THROUGH THE SEA ICE

We learned that algae live at the bottom of sea ice, which can be covered by snow. We also learned that, as plants, algae need sunlight to grow. But how is the sunlight capable of making it through the thick ice and snow to finally reach the little algae, to give them energy? The layer of snow is made of a large number of snowflakes packed together. Most of the sunlight that hits the snow is reflected back to the atmosphere, because the snow almost acts like a mirror. This is why it is always hard to look at the bright snow when the sun shines. Just like in the atmosphere, some of the sunlight is absorbed by the snowflakes, warming up the snow and contributing to its melting. It is much more difficult for the sunlight to pass through snow than to pass through the atmosphere though, because the snowflakes are more densely packed than the tiny gas molecules in the atmosphere. However, some rays find their way through. Those sun rays that make it through the snow layer will then encounter the sea ice below. Sea ice is ten times easier for the sun rays to cross than the snow is, since the ice is usually clearer than snow, with fewer particles and no snowflakes. But the sea ice is usually thicker than the snow, which again makes it harder for the sunlight to reach the algae's living place. Eventually, some of the sun's rays reach the bubbles where the algae live, making it possible for the algae to enjoy a bit of sunlight. But that is not the end! Once the sun's rays have filled the algae with energy, some leftover rays continue their journey deeper into the ocean water, giving their energy to other plants and animals until all the light rays are used up (Figure 2).

WHAT ABOUT THE FUTURE OF ALGAE?

Many activities that we do as humans have led to pollution, resulting in a heating of the atmosphere called **climate change** or **climate warming**. Climate warming can already be measured today and will continue for a long time into the future. It is important for us to understand what this warming will mean for the different regions of the planet, including the Arctic. As it turns out, the Arctic is warming faster than the rest of planet, leading to less snow cover and thinner sea ice. As a consequence, it is easier for the sunlight to find its way through the ice to reach the algae. For the algae, this means that, in the future, there will most likely be more light available, and thus more energy to use to grow. But, scientists from all around the world have calculated that, sometime in the future, the sea ice will very likely disappear completely each summer. If the sea ice disappears each summer, there will be no housing for the sea-ice algae to live in. This means that climate change is a big threat to sea-ice algae.

CLIMATE CHANGE/CLIMATE WARMING

Worldwide increase in temperature and change in climate as response to human activities.

Arctic research tries to understand the consequences of climate change for the Arctic, the atmosphere, the sea ice, the ocean, the plants and animals, and the humans. Our focus is on the sea-ice algae and the place they live, which is the sea-ice cover of the Arctic Ocean. We tell many people about our work and what we have discovered about the changes in the Arctic, so that people, including politicians, can have a better idea of what is happening now and what might happen in future. This knowledge will help us to make the proper decisions for the future of our planet.

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YOUNG REVIEWERS

ECOLE PRIMAIRE PAUL BAUDRIN, AGE: 10

At the Aslonnes school, there are five classes for children from 3 to 10 years old. In our CM2 class (fifth grade), we are 12 girls and 10 boys. We have everything we need to work and to do sports. The pupils are very intelligent and very wise and the teachers are very nice. We were very interested in the topic of sea ice. Maybe some students will become scientists.

AUTHORS

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Dr. Gaëlle Veyssiere is a sea ice scientist working at the British Antarctic Survey in the UK. Gaëlle has always been fascinated by snowy and icy surfaces on Earth and beyond. After studying snow in the French mountains using satellite data during her Ph.D., she decided to study sea ice and snow in the Arctic and the light journey through them. To do that, she has been doing fieldwork, working with collected and satellite data, and also models.

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Dr. Frank Kauker from education I am a theoretical physicist. In my diploma I "looked" at the smallest particles of matter we know about, at quarks. After the diploma I wanted to work in areas of more social relevance and made my Ph.D. on climate change in the North Sea. In the last years I was mainly concerned with the fusion of earth observations (*in-situ* and satellite) with computer models for better predictions of sea-ice conditions in Polar regions. This is as well my contribution to the project EcoLight: I help to utilize EcoLight observation in a sea ice-ocean computer model.

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I am a physical oceanographer. My main interest is to understand how the oceans move, how they develop over time, and interact with the sea ice, the atmosphere, and also how this impacts marine plants and animals. My main research region is the Arctic, and to investigate its ocean, ice, and atmosphere system I use computer models and measurements. In the project EcoLight I work with biologists and other polar researchers to understand the impact of a reducing Arctic Sea Ice cover on ice algae.

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Julienne C. Stroeve received a Ph.D. in geography from the University of Colorado Boulder, in 1996, for her work in understanding Greenland climate variability. Subsequently she became a senior research scientist at the National Snow and Ice Data Center (NSIDC) at the University of Colorado, a Professor at University College London and more recently a Canada 150 Chair at the University of Manitoba. Her Arctic research interests are wide-ranging, and include remote sensing, sea ice forecasting, atmosphere-sea ice interactions, climate change, and impacts within and beyond the Arctic.

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Dr. Jeremy Wilkinson studies the frozen ocean in the Arctic and Antarctic. He works for British Antarctic Survey, Cambridge, UK. Over the past 25 years he has organized and participated more than 20 polar field expeditions, and during this time he has witnessed the loss of almost half the summer Arctic sea ice. Jeremy has a lot of experience in working with scientists from many countries, and in many different fields of science. He enjoys an excellent working relationship with the international scientific community and other stakeholders in the Polar regions.

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Hauke Flores studied biology in Hamburg. Afterwards, he worked as a fisheries observer (a person recording the fish caught with commercial fishing vessels). During his Ph.D. thesis at the University of Groningen (2003–2009), Hauke studied animals living at the sea-ice underside in Antarctica. In 2012 he moved from the Netherlands back to Germany. Here, he headed the Young Investigators Group *Iceflux* at AWI. Since 2017, Hauke has a permanent position as a scientist at AWI. Hauke has participated in 12 expeditions to the Antarctic and Arctic Oceans.

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Marcel Nicolaus has a strong expertise in physical properties of snow and sea ice in the Arctic and Antarctic from field observations, numerical simulations, airborne measurements, autonomous platforms, and remote-sensing data. He has joined more than 20 field campaigns to Arctic and Antarctic sea ice in different seasons. Currently, he is employed as a senior scientist at the AWI, and he is/was PI in different national and international projects studying linkages of sea ice with the atmosphere and ocean.

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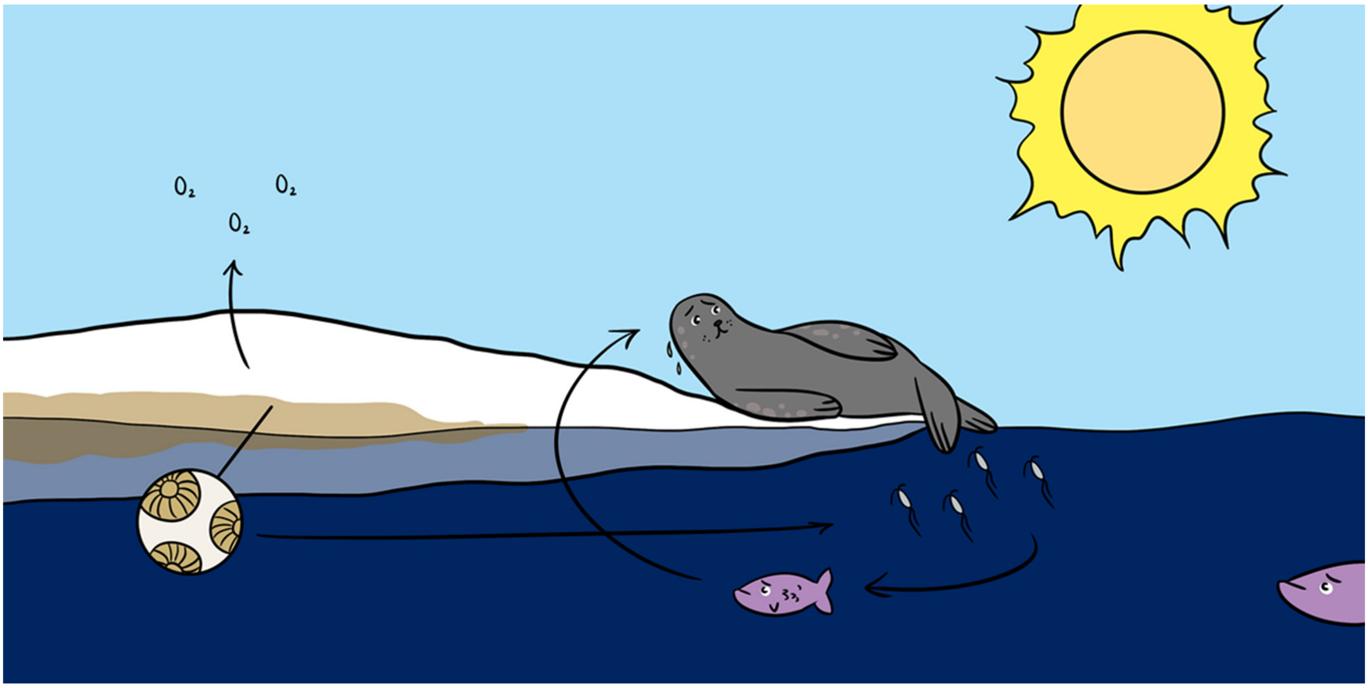

THE BOTTOM OF THE ARCTIC'S FOOD WEB IS OF TOP IMPORTANCE

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As our planet's climate warms, its most rapidly changing region is the Arctic Ocean and surrounding seas. Warming causes many changes, including the melting of sea ice and a decline in the amount of water that is covered by ice. These changes impact organisms at every level of the food web. In this article, we explain how changes in temperature affect the quality of food available for animals that live in the Arctic. We focus on changes near the bottom of the food web, involving tiny plants that dwell inside and below sea ice, and tiny animals that drift in the Arctic seas. Shifts in the abundance and quality of the smallest organisms in the Arctic Ocean affect larger organisms, such as polar bears and whales. Changes at the base of the food web must be considered if we want to protect the creatures that call the Arctic home.

HOW A CHANGING CLIMATE AFFECTS THE ARCTIC

Since the start of the Industrial Revolution, over 200 years ago, our planet's climate has changed drastically. Temperatures have soared at a faster rate than any other time in the past 65 million years! At the most northern and southern tips of our planet are the polar regions, the Arctic and the Antarctic. These are the coldest regions of Earth, where temperatures average well below 0°C. In winter, the top layer of the ocean freezes, creating what is called sea ice. Sea ice can range from paper thin ice, which melts very quickly, to incredibly thick ice that reaches heights of 3 m and can survive for many years. Sea ice has a cooling effect on the climate, acting as a refrigerator and keeping the rest of the planet at habitable temperatures.

As the temperature of our planet has increased, the environment has reacted in unique and alarming ways. In polar regions, large areas of sea ice are melting. The once snowy, white polar regions are being transformed into large areas of blue, open ocean. The warming of the polar regions has created a lot of questions that need answering. So, let us shed some light on how rising temperatures could affect the Arctic's marine ecosystem.

WHY ARE PHYTOPLANKTON SO IMPORTANT?

At the base of the marine ecosystem, we find very small, but very important, plant-like creatures that drift in all seas. These creatures are called **phytoplankton**. Due to the microscopic size of phytoplankton, they are measured on the scale of microns (μm). One micron is 10,000 times smaller than a centimeter!

Phytoplankton typically live in what we call the **euphotic zone**, simply put, the depths where there is enough light for their **photosynthesis**. Through photosynthesis, they take in carbon dioxide (CO_2) from the atmosphere and produce oxygen, just like plants on land. Together, all the phytoplankton in the world's oceans produce half of the Earth's oxygen. This is an immense amount of oxygen considering that phytoplankton make up <1% of the world's plant **biomass** [1]! In comparison, large plants like trees make up around 70% of global plant biomass yet produce about the same amount of oxygen as microscopic phytoplankton[1] . To demonstrate just how hardy phytoplankton are, it is worthwhile to note that they have been around a pretty long time. The first sign of phytoplankton was preserved in rocks from western Australia around 3.5 billion years ago!

Diatoms are the largest phytoplankton in our oceans (Figure 1). They can be circular or elongated plants and are responsible for almost 20% of the Earth's photosynthesis. Though diatoms primarily live in the open ocean, they also thrive in bizarre places. Large masses of diatoms have been found within the sea ice of both polar regions, dwelling

PHYTOPLANKTON

A drifting plant that performs photosynthesis.

PHOTOSYNTHESIS

A process in which plants use the sun's energy to convert carbon dioxide and water to oxygen and sugar.

BIOMASS

The total weight of an organism, or group of organisms in a specific region.

1 https://www.changing-arctic-ocean. ac.uk/

DIATOM

A large type of phytoplankton that is an important food source for zooplankton.

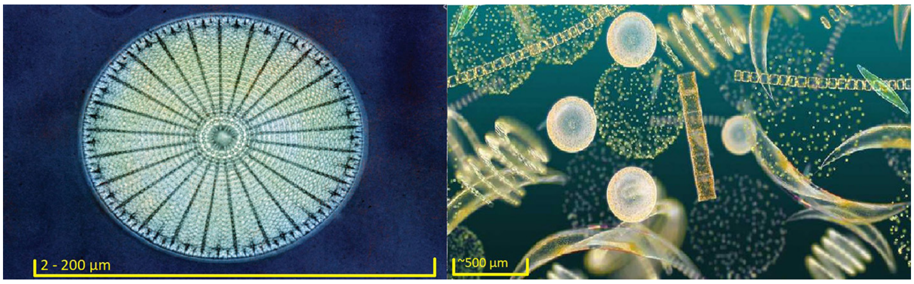

Figure 1

Figure 1

A circular diatom (left)[2] and a phytoplankton community (right)[3] Scale bars are approximations of size.

[2] https://www.gercekbilim.com/inanilmaz-elektron-mikroskopu-fotograflari-2/diatom-sem/

[3] https://ethz.ch/de/news-und-veranstaltungen/eth-news/news/2019/05/weltweite-planktonverteilung.html

inside salty, liquid, ice channels that have enough nutrients and light for them to perform photosynthesis. When diatoms are found in ice they are no longer classified as phytoplankton. As they are fixed in one place and do not drift we call them ice-dwelling algae or simply ice algae. They are often trapped in the ice as the top layer of the ocean starts to freeze. To find ice algae, ice cores roughly 10 cm in diameter are drilled out of the ice. Figure 2 shows the bottom of an ice core that has an abundance of algae inside.

WHAT EATS PHYTOPLANKTON?

ZOOPLANKTON

A drifting animal unable to swim against an ocean current.

Zooplankton are the "middlemen" of the Arctic, performing the essential role of distributing nutrients to creatures throughout the food web as they are eaten by larger predators (Figure 3). At some point in their lives, crabs, fish, and squid are all ocean drifters, and therefore termed zooplankton. Diatoms are a major food source for many zooplankton, because they contain many nutrients that give zooplankton the energy and raw materials to carry out activities, such as growing and reproducing.

As sea ice melts in summer, nutrients stored in the ice are released back into the ocean. Light also becomes more available because there is less sea ice to reflect the light back into the atmosphere. These spring changes favor phytoplankton, zooplankton, and everything that consumes these bottom-of-the-food-web residents. Since zooplankton eat diatoms, the zooplankton themselves become nutritious for larger animals, such as fish, seabirds, and whales [2]. If zooplankton were not present, the rest of the ecosystem, including humans, would face a great loss of food. Humans in Inuit communities have relied on fish (zooplankton predators) and seals (fish predators) in the Arctic for over 10,000 years!

There is a dirty aspect of zooplankton that is particularly important—their poo. When zooplankton excrete their bodily waste, it becomes a food source for many other creatures. If it does not get eaten, it can end up in the seabed where it stores carbon for millions of

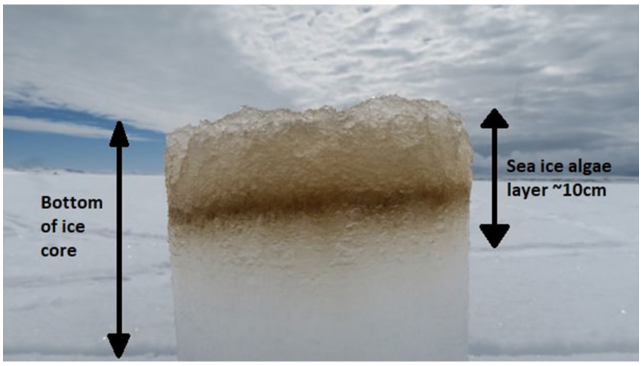

Figure 2

Figure 2

An ice core showing sea ice algae (brown layer inside the ice), including diatoms, dwelling within the bottom 10 cm of the ice[4].

[4] http://www.antarctica.gov.au/science/climate-processes-and-change/oceans-and-marine-ice-in-the-southern-hemisphere/measuring-algae-in-the-fast-ice-research-blog/sea-ice-algae-project-blog/blog-8-first-ice-algae

years, slowing down the process of climate change, and keeping our planet cool.

One group of zooplankton found in marine ecosystems worldwide is particularly noteworthy. The **copepods** were given their name due to their "pods" (or feet), which are shaped like the oars used for rowing a boat. Their oar-like feet (Figure 4) help to give these microscopic animals superhero powers! Copepods could win prizes for having some of the most outstanding features in the animal kingdom. Copepods are the strongest animal, the fastest jumpers, and may be the most numerous type of animal on the planet! The favorite food of many copepods is phytoplankton, which must live near the ocean surface where there is enough sunlight for photosynthesis. Feeding on phytoplankton is good, but not always safe; fish, birds, and other predators also hunt in the well-lit surface water, and they are waiting for copepods to make a mistake. Every day, copepods deal with the threat of predators by only entering the shallow water at night, when there is no light. After eating, copepods quickly migrate down to deeper, darker waters before shallow-water predators can see them. This daily migration of copepods and other zooplankton is the largest migration of biomass on the planet, a humongous daily movement spanning depth of tens, hundreds, or thousands of meters.

COPEPODS

A type of zooplankton with oar shaped feet. A very abundant type of copepod is called *Calanus*.

Some of the most abundant copepods in the Arctic Ocean are members of a group called **Calanus**. Packed with nutritious fats after intense spring and summer feeding, the Calanus copepods are so nutritious that some seabirds, fish, and whales travel massive distances across the oceans every year to gorge on them, typically in spring and summer. When most of the phytoplankton and zooplankton have been eaten, many of the birds, fish, and mammals leave the Arctic, to return the following year (but not all).

CALANUS

Some of the most abundant and nutritious copepods in the Arctic Ocean belong to this group.

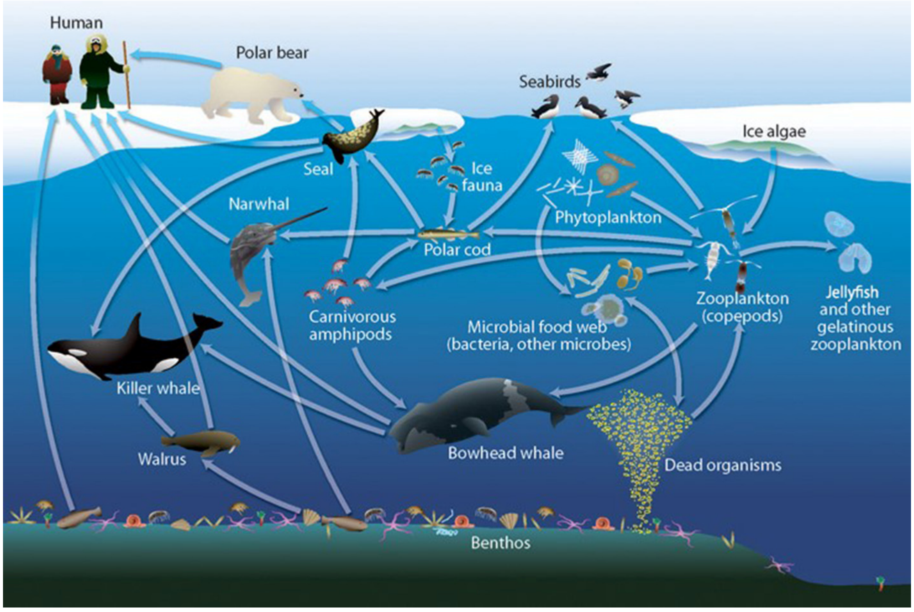

Figure 3

Figure 3

The Arctic's marine food web [2]. Phytoplankton and ice algae are eaten by zooplankton, and in turn, zooplankton are eaten by polar cod, seabirds, and the bowhead whales. This shows how both phytoplankton and zooplankton are an incredibly important food supply to the rest of the Arctic's ecosystem.

THE DARKNESS

The dark months of winter may not be the best time to be an herbivore dependent solely on photosynthesising plants for survival! Some copepods become omnivores in the winter, while others stop eating altogether and enter hibernation in safe waters far below the sea ice. Intense feeding during peak phytoplankton abundance is crucial for building the necessary fat stores to hibernate during winter. Copepods can look very different in February (after a winter of hibernation and starvation) compared to June (after feeding). In the Arctic, waking up before the phytoplankton **bloom** can be beneficial to copepods. It allows them to feed on diatoms that hang and fall off the bottom the sea ice in spring. Following months of hibernation, an individual Calanus typically appears skinny, with limited fat reserves. It is only after feeding in spring and summer that a *Calanus* copepod can replenish its fat stores to their former glory (Figure 4) [3]! After their return to algae-rich surface waters in the spring, many successful copepods reproduce during the spring ice algal bloom, allowing their offspring to hatch during the phytoplankton bloom that occurs below the ice a few months later [3]. This may be essential for their offspring to survive.

BLOOM

Rapid growth of algae or phytoplankton.

THE FUTURE

Researchers believe that if *Calanus* copepods failed to eat ice algae, the size of the copepod population could be drastically reduced. As sea ice declines due to climate change, this important food source for copepods is removed. Over long time scales, sea ice loss and other factors could decrease the availability of nutrients for the

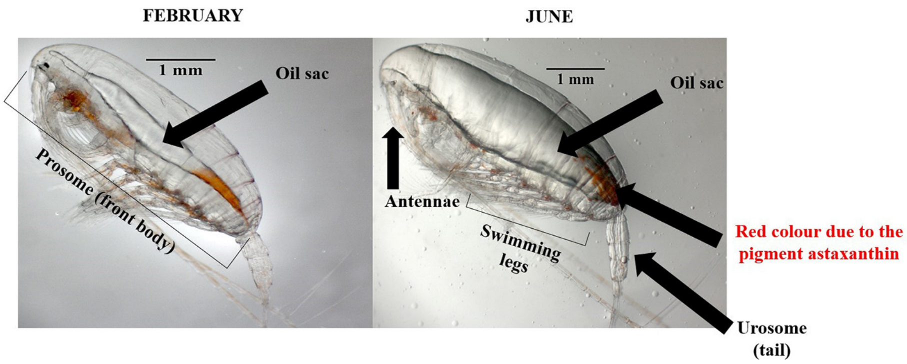

Figure 4

Figure 4

Calanus copepods sampled in February (left) and June (right). Though the lengths of the two copepods are relatively similar (4.4 and 4.8 mm), the February copepod is smaller overall than the June copepod, and the February animal, which is approaching the end of hibernation, also contains less fat in its oil sac (2019).

phytoplankton that are trying to grow below the ice [4]. This decrease of food for phytoplankton could mean that smaller phytoplankton would become more numerous than bigger, more nutritious diatoms. So, instead of having an abundance of high-quality food like large diatoms, copepods in a warmer, ice-free Arctic might be forced to eat less nutritious, smaller phytoplankton. Scientists are already seeing smaller-sized organisms in both the copepod and phytoplankton communities [5].

PROJECTED CHANGES IN THE ARCTIC AND WHAT WE CAN DO TO HELP

As the Arctic region changes, it is likely that we could see food stocks, such as diatoms and other phytoplankton decline, while also becoming smaller and less nutritious. Changes in the lowest part of the food web can have immense consequences for larger animals. Extinction of species at the bottom of the food web can be terrible news for specialized predators that have evolved to eat them. Changes in the amount and type of plankton affect humans and animals in many direct and indirect ways, ranging from changes in air quality, to how we interact with the environment and its resources. With less phytoplankton in the Arctic, CO_2 concentrations in the atmosphere would increase causing our planet to continue warming.

As a society, we need to be more aware of the fact that our activities at home, work, or school can all affect ecosystems in places that are far away from us. Small changes, such as walking or cycling instead of driving can drastically help to limit CO_2 emissions. Research programs like the Changing Arctic Ocean[1], based in the UK, are providing governments and the public with the most up-to-date information on biological changes in the Arctic. Two groups from Changing Arctic Ocean have collaborated on writing this manuscript, and we have additional resources available if you would like to learn more[5,6].

[5] https://www.changing-arctic-ocean.ac.uk/project/eco-light/

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YOUNG REVIEWERS

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We are a synthetic biology team with the international Genetically Engineered Machine (iGEM) in Lima, Peru. We are the only high school team in Latin America and are proud of our work with creating a detector for cadmium using bacteria. Most of us are second language learners and the age range of our group is 14–17 years old. We love GMOs!

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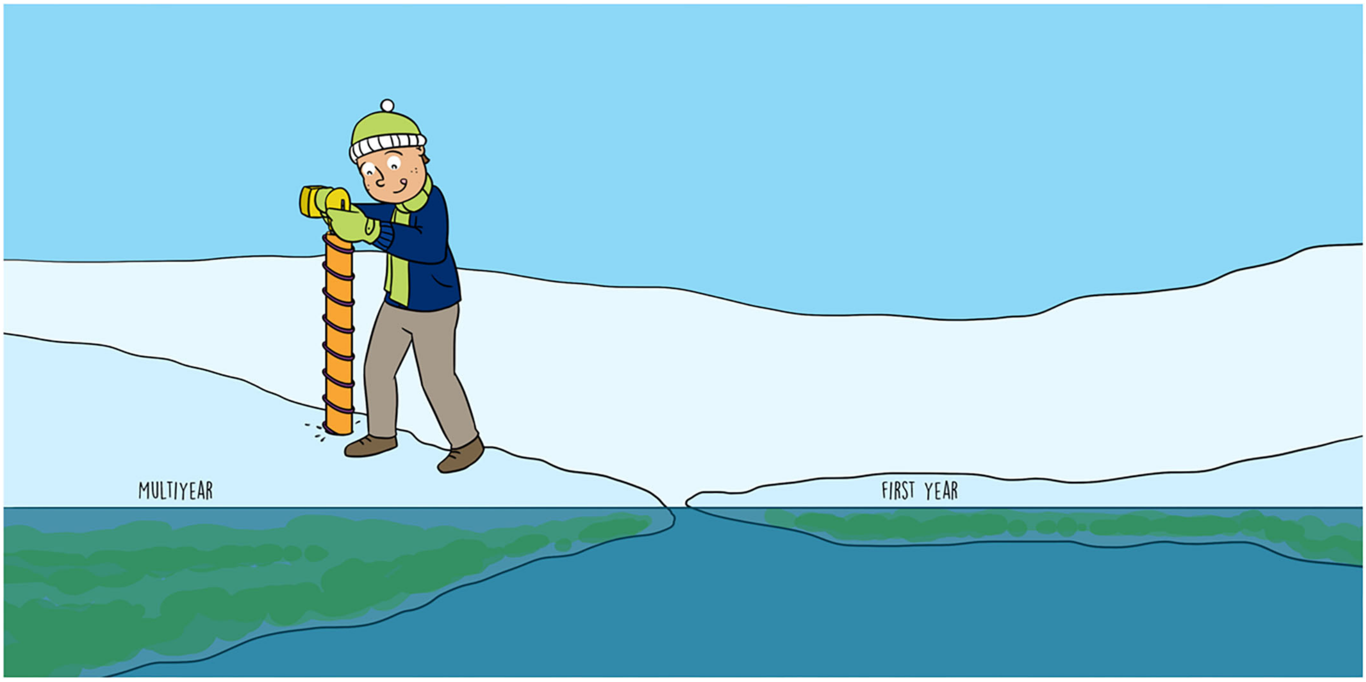

HOW MELTING ARCTIC SEA ICE CAN LEAD TO STARVING POLAR BEARS

Doreen Kohlbach** and Benjamin A. Lange

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AGES: 15–16

Sea ice is an important habitat for many organisms, from the microscopic up to large mammals like seals and polar bears. Small animals called zooplankton can feed directly on microscopic plant-like sea-ice algae. Larger animals, such as fish can, in turn, feed on zooplankton, seals feed on fish and larger zooplankton, and polar bears hunt seals. In this way, energy is transferred from algae all the way up the food chain to polar bears. Rising temperatures have resulted in changes to Arctic sea-ice habitats. These changes will affect top predators' habitats for hunting, feeding, and breeding, and will change the energy transfer from sea-ice algae up through the food chain. By studying the fat content of algae and animals, we found that sea-ice algae ensure the survival of many Arctic animals. Thus, changing sea-ice habitats can result in empty stomachs for zooplankton and, consequently, for top predators.

SEA ICE: A COZY HOME FOR MICROSCOPIC ORGANISMS

During autumn and winter, the extremely low temperatures in the Arctic result in the formation of sea ice that floats on the ocean surface. Due to the presence of salt in seawater, small pockets, called brine channels, are formed within the sea ice. These brine channels are very important features of sea ice, because they enable plants and animals to live in, and to move throughout, the ice. One group of microscopic plant-like organisms growing within and underneath the sea ice is called **sea-ice algae**. To grow and reproduce, sea-ice algae require light for photosynthesis. In photosynthesis, the algae absorb carbon dioxide (CO_2) from the ocean and atmosphere and transform it into fats and sugars, using energy from sunlight. These compounds serve as an energy source for organisms that feed on sea-ice algae. During Arctic winter, there is not enough light for photosynthesis, so algae cannot grow. In spring, the light increases, and sea-ice algae grow rapidly, which is referred to as the ice-algal bloom. The higher temperatures in spring soften the sea ice and the bottom ice starts to melt. Sea-ice algae in the bottom of the sea ice are then released into the water, where they are eaten by highly specialized animals, called grazers.

SEA-ICE ALGAE

Algae that live within the sea ice, mainly close to the sea ice-water interface.

Thirty years ago, the Arctic Ocean was dominated by very old, thick sea ice called multiyear ice. Multiyear ice is ice that has survived one or more summer melt seasons (Figures 1a,c). Most of this multiyear ice was 5–10 years old and reached thicknesses over 10 m. Today, this old, thick, multiyear ice has almost disappeared, and the remaining multiyear ice is dominated by 2–4-years-old ice with 2 to 5 m ice thickness [1]. This remaining multiyear ice is now found primarily in a small area between Canada, Greenland, and the North Pole—the so-called Last Ice Area. As the Arctic sea-ice habitat continues to change, the Last Ice Area may become an important refuge for animals that depend on sea ice for survival.

Because of its presence year-round, multiyear ice is a particularly important habitat within the Arctic ecosystem [2]. Due to climate change, however, multiyear ice is being replaced by thinner, younger sea ice called first-year ice. This is sea ice that has NOT survived a summer melt season and is thus <1 year from formation (Figures 1a,b). Multiyear ice and first-year ice provide different habitats for Arctic animals. For example, sea-ice ridges, which form when ice floes crash into each other (just like mountains form when tectonic plates crash together), are unique habitat features that we know very little about. However, we know that sea-ice ridges form more easily when the ice is thinner, so it is likely that the number of sea-ice ridge habitats will increase as multiyear ice is replaced by thinner first-year ice.

With our research, we try to shed some light on the importance of different sea-ice habitats for marine animals. We try to understand

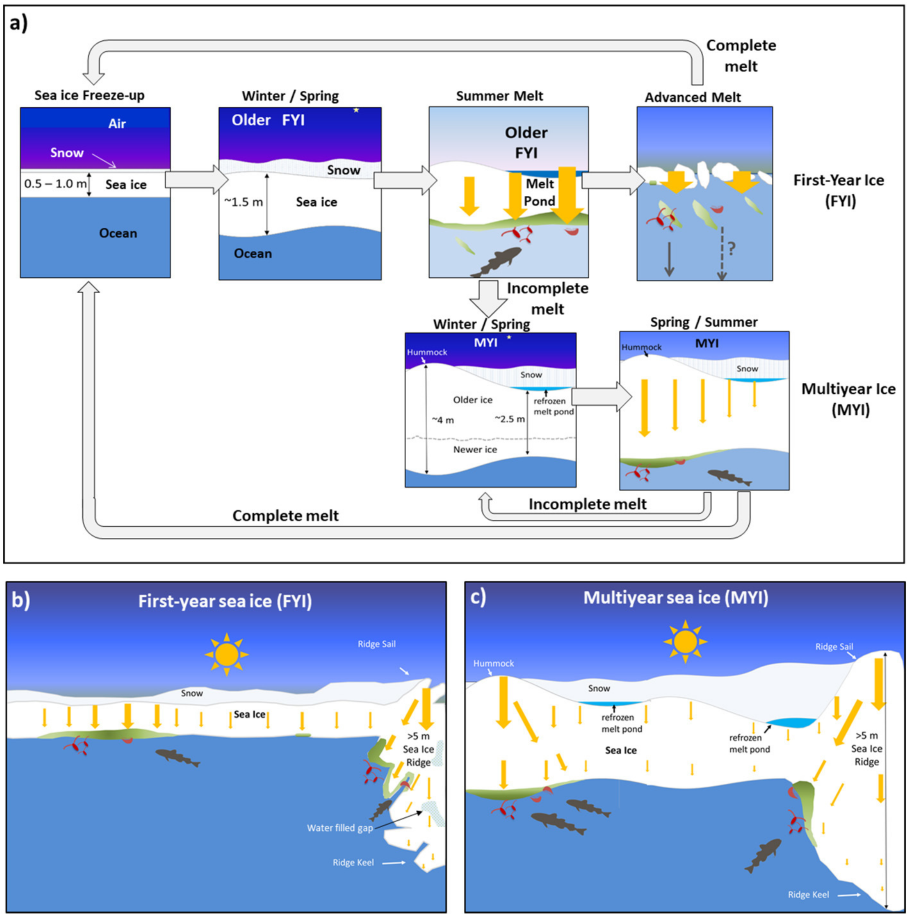

Figure 1

Figure 1

Comparison of first-year and multiyear sea ice. **(a)** Development of sea ice and snow accumulation, showing the transition from first-year to multiyear sea ice. **(b)** First-year sea ice, and **(c)** multiyear sea ice have different habitat properties. Size of yellow arrows corresponds to amount of light. Green patches are sea-ice algae.

what will be on the grazers' menu if there is less sea-ice algae in the future Arctic Ocean, and how that will impact top predators.

WHO EATS SEA-ICE ALGAE: THE ARCTIC FOOD WEB

In the Arctic Ocean, sea-ice algae and algae that live in the open water (called **phytoplankton**) represent the base of the marine food chain. These algae are called primary producers, because they convert energy from the sun into chemicals that can be used by the organisms higher in the food chain, called consumers. After algae, the next **trophic level** in the food chain includes small animals called **zooplankton** that feed on sea-ice algae, phytoplankton, or both. Further up the food chain, larger zooplankton feed on smaller zooplankton. These larger zooplankton are a tasty energy source for fish, which are, in turn, on the menu for seals. Lastly, seals are consumed by polar bears. Seals and polar bears are called top predators, which means they represent the endpoints of the food chain. In reality, the interaction of the members of the food chain is a bit messier, because many animals have more than one food source, which is why the who-eats-whom connections are usually called a

PHYTOPLANKTON

Algae that live in the water column, and that are transported with the ocean currents.

TROPHIC LEVEL

"Who eats whom"—the position of an animal within a food web. Animals feeding on algae are lower in the food chain than animals feeding on both algae and other animals or strictly on other animals.

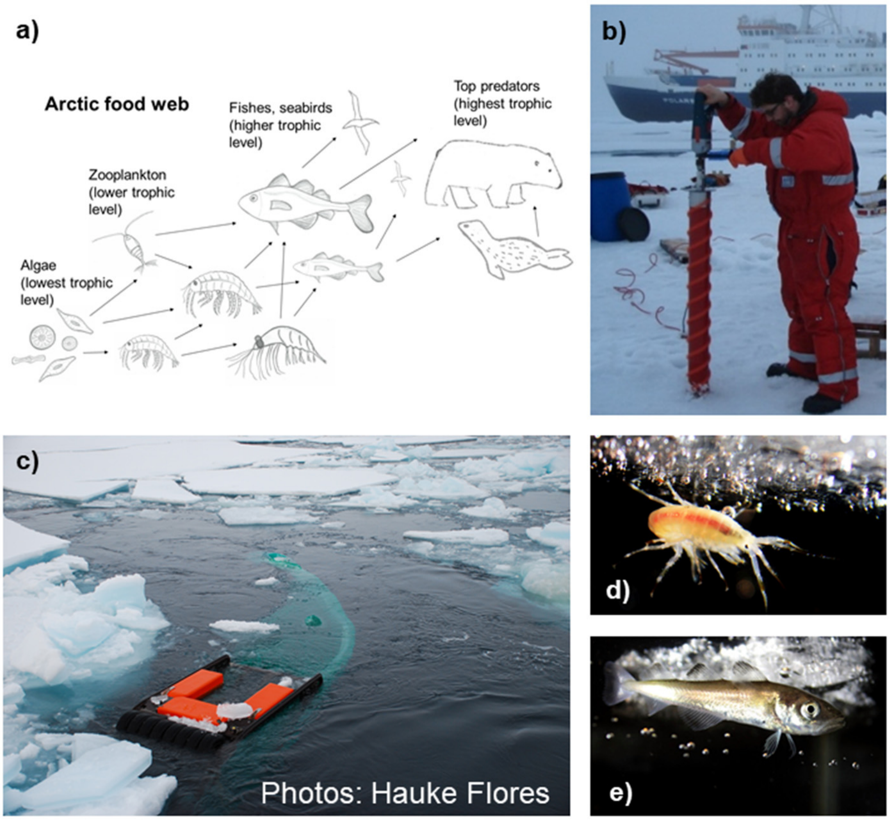

Figure 2

Figure 2

(a) Simplified structure of the Arctic food web. Energy is transferred from the lowest trophic levels to the top predators. **(b)** Benjamin A. Lange takes sea-ice cores (in the background: German icebreaker *Polarstern*). **(c)** Surface and under-ice trawl (SUIT) for sampling organisms living directly underneath the ice. **(d)** An example of a large zooplankton, *Gammarus wilkitzkii*, that is a sympagic amphipod. **(e)** Polar cod *Boreogadus saida* feed on copepods and amphipods.

food web (Figure 2a). Within the marine food web, energy is transferred from one trophic level to another in the form of carbon, which is an important component of energy-containing molecules. Top predators are indirectly dependent on sea-ice algae and phytoplankton because the carbon produced by these algae ends up in the top predators' bodies. Almost all processes within the food web are connected to each other. That means, if something changes at the base of the food web, there can be a domino effect all the way up to seals and polar bears.

ZOOPLANKTON

Small marine animals that drift with the ocean current. They are an important link between algae and higher trophic levels by transferring energy along the marine food chain.

HOW DO WE KNOW WHAT WE KNOW?

Polar researchers use ice corers, long tubes with sharp blades at their ends (Figure 2b), to drill holes into the ice to extract sea-ice cores for study. Since sea ice can be several meters thick, drilling ice cores is very time-consuming and labor-intensive! To collect zooplankton and fish, we use nets that are lowered into the water. Some animals live at the sea ice-water interface, directly underneath the ice. These animals can be caught by scuba divers or with special nets that can move directly underneath the ice (Figure 2c). Other zooplankton are **pelagic**, which means they spend most of their time in the open ocean (NOT near sea ice) at different water depths. To obtain samples from

PELAGIC

Lifestyle of animals that spend most of their lives in deep water. Pelagic animals feed on phytoplankton and can also use sea-ice algae as a food source.

seals or polar bears, researchers work closely with local Inuit hunters, who can provide muscle, blubber, and organ samples.

Next, in the lab, we investigate the lipid content in the algae and animals we collect, which can tell us about where the carbon in the animals' bodies originated from. Lipids are fats, and they are made of large carbon-containing molecules called fatty acids. Ice algae and other primary producers make certain fatty acids called marker fatty acids, which are transferred unchanged to animals when the algae are eaten, all the way up to seals and polar bears. Sea-ice algae and phytoplankton can each produce their own set of marker fatty acids. This gives us the great opportunity to distinguish the origin of the carbon in the consumers, meaning we can tell if the organism of interest prefers to eat sea-ice algae or phytoplankton, or a combination of both.

MANY ARCTIC ANIMALS NEED SEA-ICE ALGAE FOR THEIR SURVIVAL

Most animals have mixed diets and receive their energy from both sea-ice algae and phytoplankton. However, some zooplankton, including small crustaceans called amphipods (Figure 2d), spend most of their lives in close association with sea ice (called a **sympagic** lifestyle). Sympagic organisms use the sea ice as a place to live, feed, and hide from predators. We found that the carbon consumed by the sympagic amphipod *Apherusa glacialis* was almost entirely from sea-ice algae [3] (Figure 3). In other words, those animals are almost 100% dependent on sea-ice algae for their survival! Polar cod (Figure 2e) is an important fish species in the Arctic Ocean, because it is a popular food source for seals and birds. Polar cod can feed on sympagic amphipods, which means this species is also highly dependent on sea-ice algae [4]. Even higher up the food chain, sea-ice algae can be important in the diets of different seals and polar bears [5, 6].

SYMPAGIC

Lifestyle of animals that live in close association to sea ice. Sympagic animals can use sea ice as shelter from predators and/or as a feeding habitat. Some animals switch between pelagic and sympagic lifestyles during different times of the year.

WHAT HAPPENS WHEN THE SEA ICE MELTS AND SEA-ICE ALGAE ARE SCARCE?

Currently, it is a bit tricky to predict how ongoing climate warming will affect the future of marine animals. For many Arctic animals, our knowledge of what, when, and how much they eat is still rather limited. We know that some species are more sensitive to climate change than others, for example sympagic animals. From our results, we can assume that the survival of these ice-associated animals, including those of low and high trophic levels, will be threatened when the sea ice disappears. However, another possibility, and one we can hope for, is that these animals will find a way to cope with the environmental changes, by finding alternative food sources or seeking refuge in

Figure 3

Maximum percentage of carbon produced by sea-ice algae in the bodies of various Arctic animals. The amount of carbon was identified using several laboratory methods [3, 4]. Sympagic amphipods are sea ice-associated crustaceans. Pelagic copepods, and other amphipods spend most of their lifecycles at greater depths.

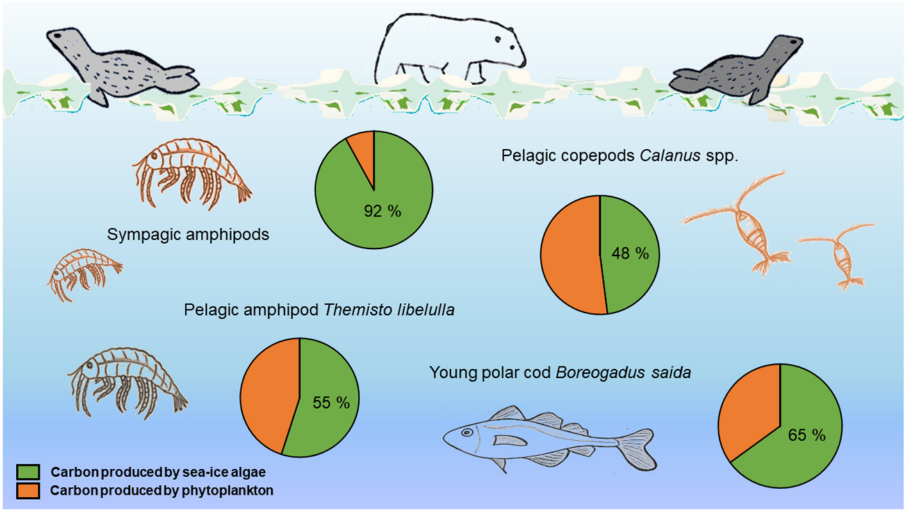

Figure 3

unique sea-ice habitats, such as sea-ice ridges. Studies like ours can help to provide a better overview of the lifestyles of Arctic animals. Our results can be linked to other studies to investigate possible changes specific to a certain region or season. To fully understand the challenges the Arctic food web will face, more information about diets and lifestyles of Arctic animals and their vulnerability regarding environmental changes needs to be collected in future studies.

ACKNOWLEDGMENTS

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ORIGINAL SOURCE ARTICLE

Kohlbach, D., Graeve, M., Lange, B., David, C., Peeken, I., and Flores, H. 2016. The importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: food web relationships revealed by lipid and stable isotope analyses. *Limnol. Oceanogr.* 61:2027–44. doi: 10.1002/lno.10351

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

Devonport High School for Girls

DEVONPORT HIGH SCHOOL FOR GIRLS (11C/2020), AGES: 15–16
We are a group of enthusiastic Year 11 students studying for our GCSE exams in the summer of 2020 and are really interested in the effects of climate change. We enjoyed finding out more about a career in science from our Science Mentor, Dr. Parry, who used to work in marine science before becoming our biology teacher.

AUTHORS

DOREEN KOHLBACH

Doreen is a Marine Biochemist with a scientific interest in polar food web interactions. Doreen was born in Germany, where she also got her Ph.D. To gain work experience abroad, she moved to Canada to study the importance of sea-ice algae for the food web in the Canadian Arctic. Doreen enjoys collecting samples in the field and analyzing them in the lab. Currently, Doreen works at the Norwegian Polar Institute in Tromsø, Norway. Here, she is involved in a large Norwegian project to study the consequences of climate change for the food web in the Barents Sea (`https://arvenetternansen.com/`). *doreen.kohlbach@npolar.no

BENJAMIN A. LANGE

Benjamin is a Sea Ice Bio-Physicist, who studies sea-ice habitat properties and consequences of climate change for sea-ice algae. Ben was born in Canada and got his Ph.D. in Germany. Ben's favorite part of being a scientist is participating in research expeditions and writing and publishing research articles in scientific journals. After working at a Canadian research institute, Ben is currently affiliated with the Norwegian Polar Institute in Tromsø, Norway. He is part of a huge international project in which the German icebreaker, *Polarstern*, will freeze into the Arctic sea ice to collect samples for an entire year (`https://follow.mosaic-expedition.org/`).

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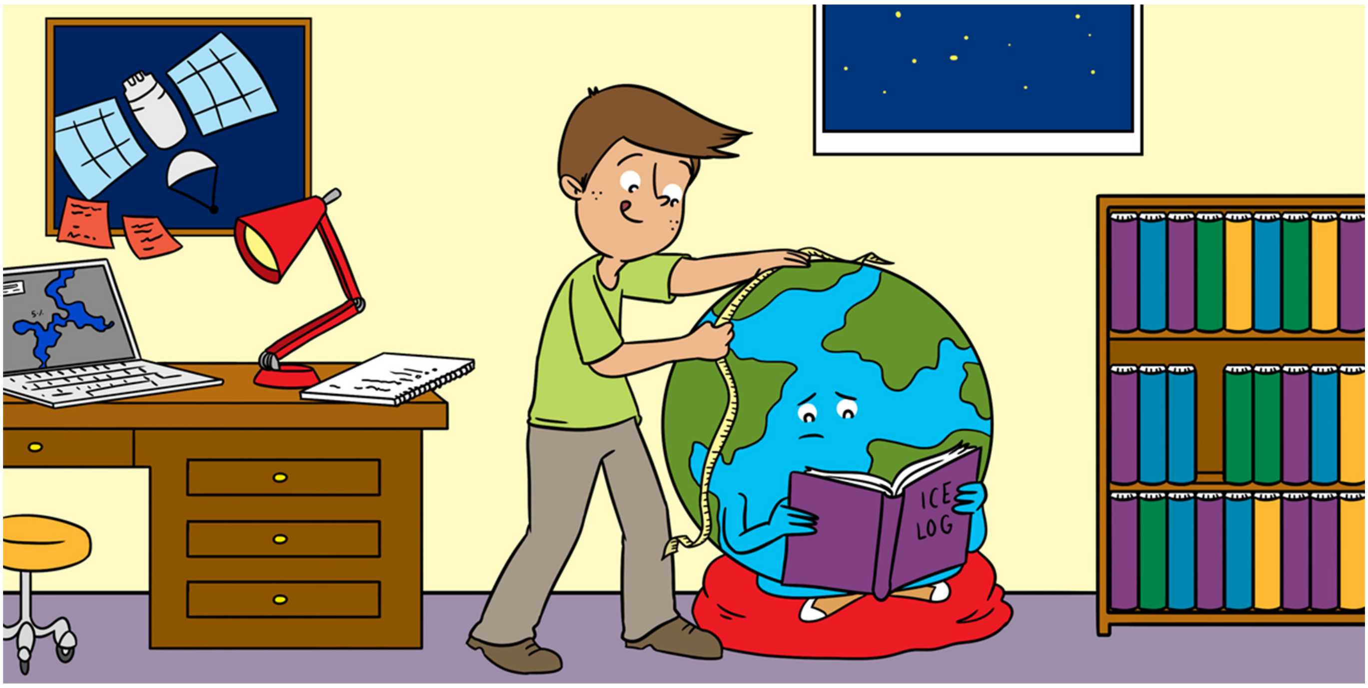

HOW DO WE TRACK CHANGING ARCTIC SEA ICE?

*Olivia Lee**

International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, United States

YOUNG REVIEWER:

ARYAN
AGE: 15

Tracking changes in Arctic sea ice is an important way to understand how the Arctic is changing. This article explains how sensors on satellites can be used to track sea ice change, by measuring the energy given off by objects on earth. We will also explain some of the limitations of this method and describe other ways to track sea ice from old whaling ship records or from working with indigenous coastal communities. Used together, all of these methods can help us get a more complete picture of changing Arctic sea ice.

WHY SHOULD WE CARE ABOUT MEASURING ARCTIC SEA ICE CHANGE?

The amount of sea ice in the Arctic has been decreasing over recent years. We care about this for many reasons, but one important reason is that ice affects life in the Arctic. If there is less sea ice in the Arctic, walruses and seals have fewer resting places on the water. Less sea ice also affects the number of tiny plants, called ice algae, that live in the ice. These tiny plants are important food for other animals in the Arctic. Measuring sea ice also helps people in the Arctic understand the dangers of low sea ice conditions that can make it dangerous for people to travel over thin or unstable ice.

HOW DO WE MEASURE CHANGING ARCTIC SEA ICE?

Sea ice covers large areas of the Arctic, and the only way to see the whole Arctic is to look at it from space. Scientists today use tools on satellites to get a wide view of the sea ice over the Arctic. One satellite-based tool that scientists use measures a type of energy called **passive microwaves**. By measuring passive microwaves from space, scientists can tell where there is sea ice, and where there is land or water.

PASSIVE MICROWAVES

Low energy microwaves that are naturally emitted by objects, and can be passively detected by sensors.

WHAT ARE PASSIVE MICROWAVES AND HOW DO WE USE THEM?

All objects on earth give out energy as microwaves. Microwaves are a type of low-energy radiation that is not related to the temperature of the object. Since all objects naturally radiate this energy they can be passively detected by sensors on satellites, hence the term: "passive microwaves." The low-energy microwaves can give us some information about the composition of the object they come from. The types of atoms in an object and how these atoms are arranged affects the energy they give out. For example, solid sea ice gives out more microwave energy compared with the ocean water around it. When the satellite data detects this higher energy area, it tells us that there is sea ice on the ocean. Clouds in the sky do not give out much microwave energy, and this makes it easy to "see through" the clouds to find sea ice using satellite equipment that can detect passive microwaves. This is an improvement over using satellites to take "regular" pictures of the earth in the visible light range, because when clouds cover the sky, visible light, which is the energy we can see with the naked eye, is blocked.

However, there are some problems with using passive microwaves to measure sea ice. Since the microwave energy given off by sea ice is so low, this tool is best used for measuring ice over large areas. This means that we can use passive microwaves to measure sea ice across the entire Arctic (Figure 1), but we have a harder time finding smaller details in the ice with this tool. For example, it is not easy to find leads, which are narrow breaks in sea ice where there is some open water. It can also be hard to measure sea ice with passive microwaves when there is very little ice. For example, when there is <10% sea ice in the ocean, there can be mistakes in the ice measurements.

NASA

National Aeronautics and Space Administration.

Satellites have helped us measure passive microwaves from sea ice since 1972. However, most scientists use satellite measurements starting from 1978. This was the year when **NASA** put a special sensor,

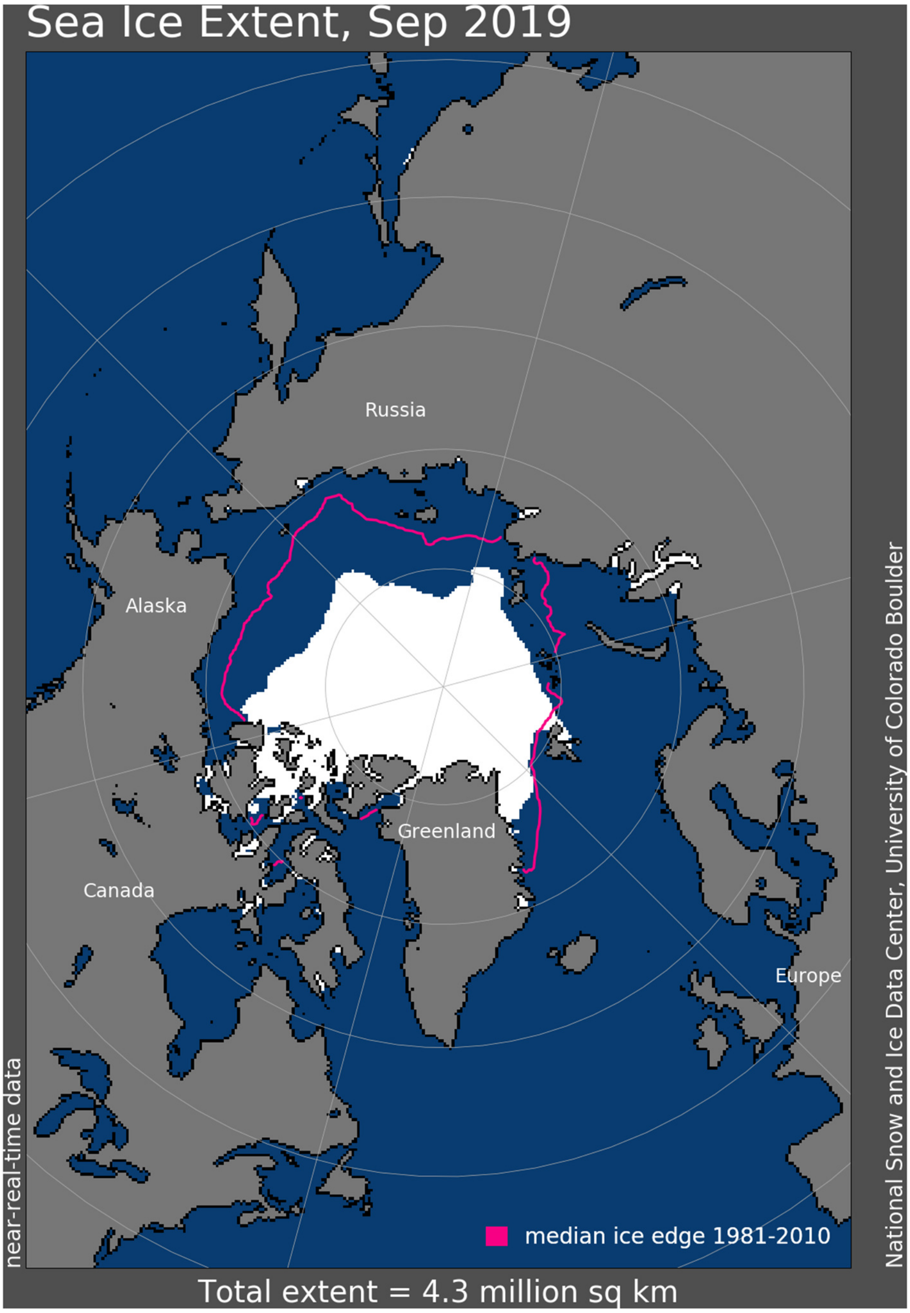

Figure 1

Figure 1

Arctic sea ice measured from passive microwaves in September 2019 (white area). The pink line shows where the median ice edge was measured between the years 1981 and 2010. Source: National Snow and Ice Data Center.

called the **scanning multichannel microwave radiometer (SMMR)**, into operation to find sea ice.

SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMMR)

This is a type of sensor used in passive microwave detection of sea ice from satellites.

HOW ELSE CAN WE STUDY SEA ICE CHANGE?

Since there are some problems with measuring sea ice by passive microwaves, scientists also study sea ice using other information. There are additional satellite tools that can be used to measure sea ice, but we will focus on a few non-satellite examples.

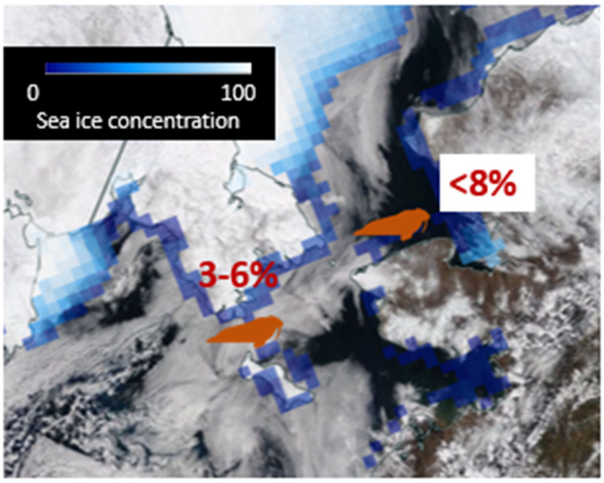

Figure 2

Figure 2

Data from several sources can be combined to give a more complete picture of sea ice. The average amount of sea ice measured from passive microwaves is reported in red numbers. Sea ice concentration ranges from just over 0% in the blue squares to 100% in the white squares. The satellite photograph shows some cloud cover, which makes it difficult to see areas of sea ice. Coastal community reports of sea ice provide locations of walruses seen traveling with the sea ice (orange walrus icons).

The Historical Sea Ice Atlas puts together information from different sources about where sea ice was found. Some information about sea ice goes back as far as 1850. Since this was long before modern satellites, scientists used old logbooks from whaling ships that reported sea ice conditions, and old maps that helped ships travel safely over the ocean.

Scientists also work together with native sea ice experts in coastal communities to measure changes in sea ice. Working with native experts, scientists can record when the sea ice starts to freeze or melt near the coast, and they can combine local expert information with what they know from satellites [1]. This is important because native experts can provide detailed information about the sea ice that is hard to obtain from satellite data. For example, native experts can tell us when and where breaks in the ice happen, they can describe the cause of large piles of ice (called ice ridges), and they can also describe when animals, such as walruses, are seen as these animals travel north with the ice during spring (Figure 2).

WHAT ARE SOME OTHER EXAMPLES OF SATELLITE TECHNOLOGY TO MEASURE SEA ICE CHANGE?

A comparison of different satellite technologies that are used to detect sea ice is shown in Figure 3. Some methods use passive energy that is reflected from objects on earth, and these methods include using visible light or passive microwaves, as described earlier. Other techniques, such as **light detection and ranging (LIDAR)** and **radio detection and ranging (RADAR)**, use active energy pulses to detect characteristics of sea ice. LIDAR uses lasers as an active energy source, while RADAR uses radio wave energy. "Active" means that energy is sent out of a platform—which could be an airplane or satellite, to bounce off objects on the earth. Then, the energy that bounces back

LIGHT DETECTION AND RANGING (LIDAR)

This uses laser pulses as an active energy source and a sensor to that captures the returning light to measure distances.

RADIO DETECTION AND RANGING (RADAR)

This uses an active energy source to emit radio waves and a sensor that receives the returning radio waves to detect objects.

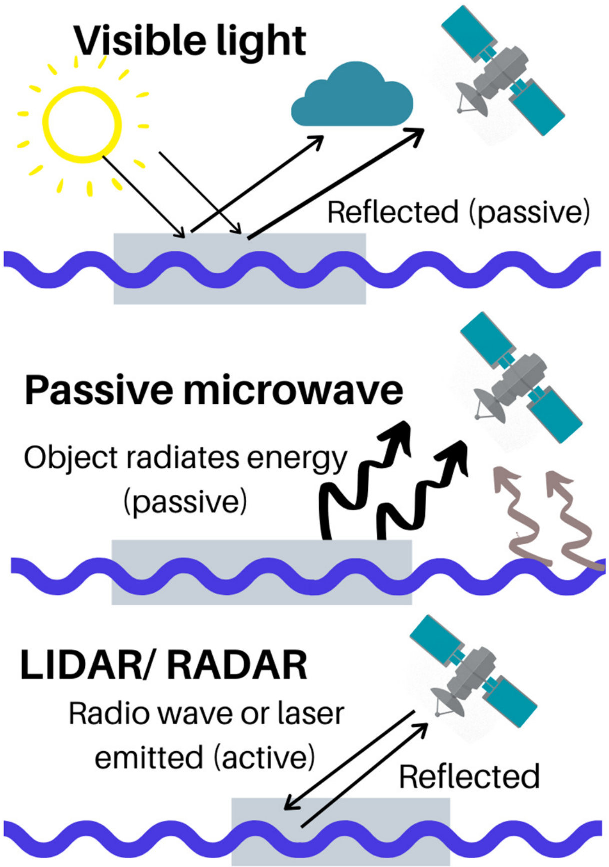

Figure 3

Ways that sensors on satellites can detect sea ice. (Top) Visible light from the sun is reflected off objects on earth and can be detected by satellites, in the form of photographs, but this is affected by cloud cover. (Middle) Passive microwave energy naturally emitted by all objects on earth can be detected by satellites. The level of energy detected tells scientists about the type of object emitting it. (Bottom) A satellite can emit active pulses of lasers (LIDAR) or radio waves (RADAR) that are then reflected back by surfaces on earth and captured by the satellite sensors.

ICESat2

Ice, Cloud, and land Elevation Satellite 2.

to the platform is detected by sensors. The recently launched NASA **ICESat2** satellite is an example of an active ice detection technique using LIDAR, in which laser beams from the satellite are used to look at sea ice thickness (NASA has more information on the laser technology here). As laser pulses emitted from the ICE-Sat2 satellite hit the surface of the earth, the number of returning photons (particles of light), and the time it takes for these photons to travel back to the satellite is used to calculate the distance between the satellite and the earth's surface. Knowing the distances between the satellite and the sea ice surface or open water, it is possible to calculate the height of the sea ice above sea level. Such technological advancements help us look at sea ice thickness, and not just sea ice cover. However, the narrow beams of the lasers are only able to capture snapshots of relatively small areas of sea ice at any given time, just as a beam of light from a flashlight can only illuminate the small areas of the dark that you point the light at.

IMPORTANCE OF OBSERVING SEA ICE

Sea ice is a core component of polar regions that has been changing rapidly over the last decade. We use a range of high-tech tools, such as satellite detections of passive microwaves, but also collaborations with native communities to observe and track how quickly the Arctic is changing. This information can then be used to help people plan how to adapt and respond to rapid Arctic change.

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YOUNG REVIEWER

ARYAN, AGE: 15
Aryan is a budding learner who enjoys reading about scientific advancements especially in the field of climate change and energy. Outside the classroom, Aryan is a fabulous football player full of energy and gusto. One day, he hopes that Manchester United can win the English Premier League, although if they go on losing to Newcastle, that day is far away!

AUTHOR

OLIVIA LEE
Olivia is a researcher at the International Arctic Research Center in the University of Alaska Fairbanks. She is interested in studying Arctic marine ecosystem change, and she frequently collaborates with Indigenous Alaska experts living along the coast to understand how sea ice change affects marine mammal distributions in

the northern Alaska. Her work is interdisciplinary and includes scenarios research on how physical environmental change, Arctic development activity, and ecosystem change co-evolves in ways that are not easy to predict. *oalee@alaska.edu

THE EARTH AND ITS RESOURCES
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VIRTUAL REALITY: USING COMPUTER MODELS TO LEARN ABOUT ARCTIC CLIMATE CHANGE

James Ward [1,2*]***, Felipe S. Freitas*** [1,2]***, Katharine Hendry*** [1] ***and Sandra Arndt*** [3]

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[2] *Biogeochemistry and Modelling of the Earth System, Université Libre de Bruxelles, Brussels, Belgium*
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YOUNG REVIEWER:

DANNY

AGE: 8

Phytoplankton are the plants of the ocean. When they die and sink, they become a source of delicious food for microorganisms, such as bacteria that live in the mud that settles on the seafloor. As these microorganisms feast on the phytoplankton, nutrients (chemicals needed for growth) stored in the phytoplankton cells are released into the water contained within the mud. These nutrients can then escape into the ocean and be used by new phytoplankton—the circle of life! However, this process is complicated and made up of hundreds of reactions that combine to produce the patterns scientists observe when on expeditions. This is where computers come in handy. We have computer models of the seafloor that can help us to understand the complicated web of reactions that underlie our observations. These models can also be used to simulate extreme conditions, to see how climate change might alter these important processes.

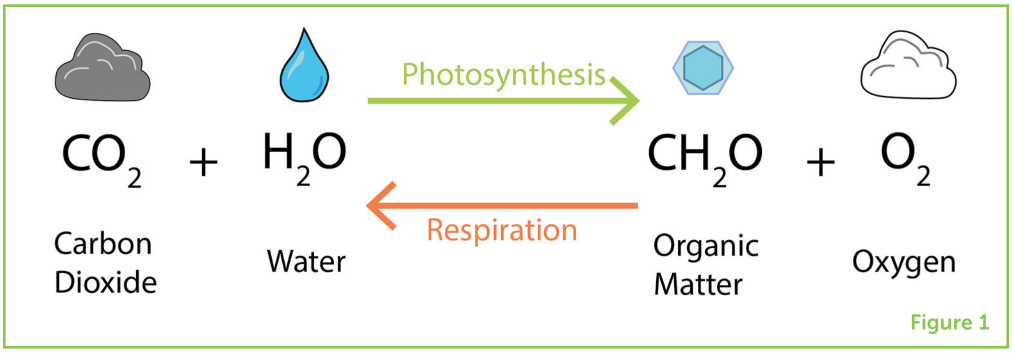

Figure 1

Photosynthesisers, like phytoplankton, use sunlight to create organic matter, shown here as CH_2O. Respiration by humans and some microorganisms uses that organic matter, along with oxygen, to produce energy. Other microorganisms can use different chemicals for respiration. Their respiration reaction is similar, but instead of O_2, the equation in the figure would contain nitrate (NO_3^-), sulfate (SO_4^{2-}), or iron ($Fe(OH)_3$).

SEAFLOOR MICROORGANISMS

Phytoplankton are the tiny plants of the ocean. You cannot see individual phytoplankton without a microscope, but they form the base of all ecosystems in the marine world, supporting everything from killer whales to polar bears. These organisms, known as **autotrophs**, survive by using energy from sunlight, in a process called photosynthesis. This is a process that takes carbon from the atmosphere (in the form of CO_2) and nutrients from the surface of the ocean and produces food for the phytoplankton to survive (Figure 1). When the phytoplankton die, they sink and can become buried in mud on the seafloor (Figure 2). At this point, they themselves become a great source of delicious food (which we refer to as "**organic matter**") for tiny microorganisms. The microorganisms that live within this muddy environment are similar to humans, in that they need to eat organic matter to produce the energy needed to survive. This type of organism is known as a **heterotroph**. As humans, we eat organic matter (fruit, vegetables) and we breathe in oxygen from the air and process everything to produce energy through a reaction called **respiration**, which is the opposite of photosynthesis (Figure 1). Some microorganisms do this too, if they live close to the ocean bottom water, which is often rich in oxygen; but many microorganisms live deep within the seafloor where there is no oxygen. These microorganisms still eat organic matter, but they have adapted to use other chemicals during respiration, such as nitrate (NO_3^-) and sulfate (SO_4^{2-}). Some can even use solids like iron minerals ($Fe(OH)_3$) [1]! The process of organic matter breakdown and the complex web of reactions that happens within the seafloor is known as **diagenesis** [2].

The diagenesis that occurs on the seafloor is incredibly important because, as the seafloor microorganisms eat, the nutrients stored in their food are released back into the ocean (Figure 2). Sometimes, when the microorganisms are using solid iron minerals for respiration, iron can also be released into the ocean water. Iron is only required in small amounts by phytoplankton, so we refer to it as a micronutrient, but it is vital for their survival and often in short supply! Thanks to diagenesis, instead of all the organic matter that lands on the seafloor

AUTOTROPH

An organism that can create its own food from simple substances from its surroundings like CO_2, usually by photosynthesis.

ORGANIC MATTER

Animal or plant based material that becomes food for microorganisms living in the seafloor.

HETEROTROPH

An organism that cannot create its own food and takes nutrition from existing plant or animal matter.

RESPIRATION

A chemical reaction that occurs in living things to create the energy they need to survive. As humans, we breathe in oxygen and use it to break down food, which releases the energy stored within it.

DIAGENESIS

The sum of chemical reactions and physical processes that change sediment when it settles in water.

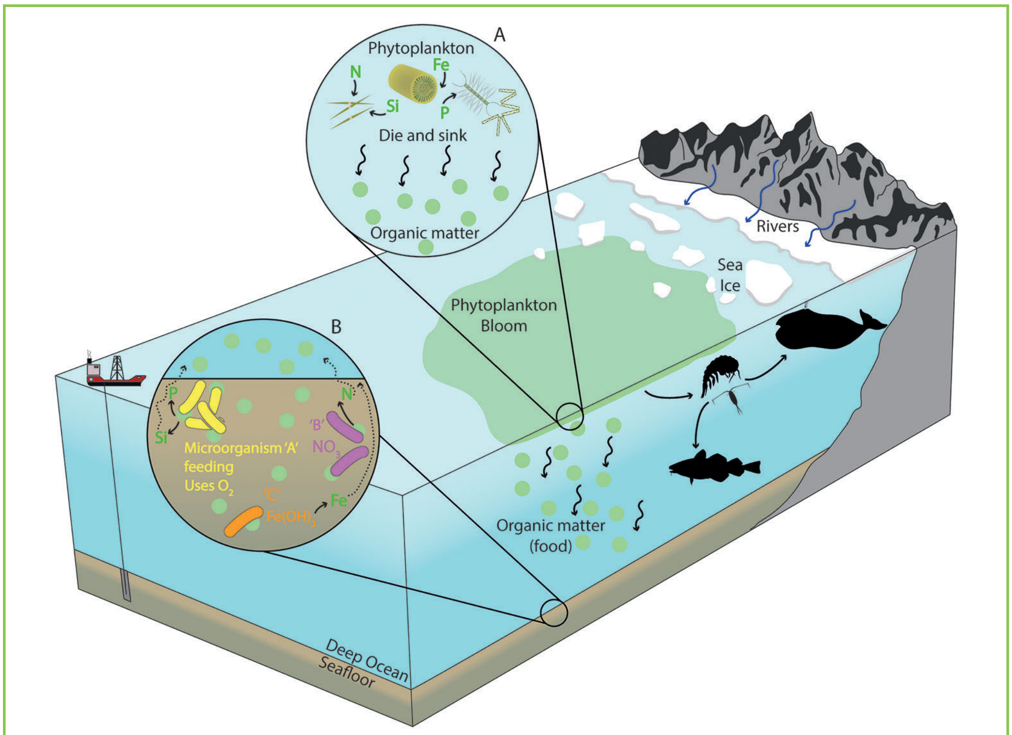

Figure 2

Figure 2

Large increases in the phytoplankton population are called blooms. The phytoplankton take nutrients [like nitrogen (N), silicon (Si), iron (Fe), and phosphorous (P)] in from the surface ocean and perform photosynthesis, then they eventually die and sink (see circle **A**). At this point, they become organic matter, a source of food for microorganisms in the seafloor. Different types of microorganisms (**A, B**, and **C**) eating the food perform respiration. Microorganism A might use oxygen for respiration, like humans, but B and C may use nitrate (NO_3^-) or solid iron minerals ($Fe(OH)_3$) (see circle **B**). As food is broken down during respiration, the nutrients originally taken from the surface by the phytoplankton are released into the mud, and eventually enter the ocean water where they can be reused.

being buried for millions of years, most of the nutrients that land there are returned to the water to be reused by new phytoplankton, to start the cycle all over again. If the seafloor microorganisms did not exist, imagine what would happen to the nutrients the phytoplankton need to take up from the surface ocean. There would be fewer nutrients available because there would be no way of recycling them! This is why we care so much about the process of diagenesis, because phytoplankton that are powered by ocean nutrients are incredibly important for taking CO_2 out of the atmosphere, which is necessary to help prevent our carbon emissions from warming the planet even more quickly.

We can study these seafloor processes by going out on ships and collecting tubes of mud, known as cores (Figure 3). We can then take this mud back to our laboratories and measure the concentration of the different chemicals in both the mud itself and in the water trapped within it, called **pore water**. This information can help us to understand what happens to the organic matter that reaches the seafloor. For example, we can measure how much organic matter there is and how quickly it is being eaten, and we can also look at how the concentrations of the different chemicals used during respiration change from top to bottom in the core. However, there are many processes that can change the concentration of these chemicals, including some that do not involve microorganisms. Therefore, even though we can measure the amounts of certain substances, it is sometimes still very difficult to determine exactly which processes are occurring in the seafloor. If we want to know how climate change

PORE WATER

Seawater trapped within seafloor mud. We can study this to learn more about the activities of different microorganisms.

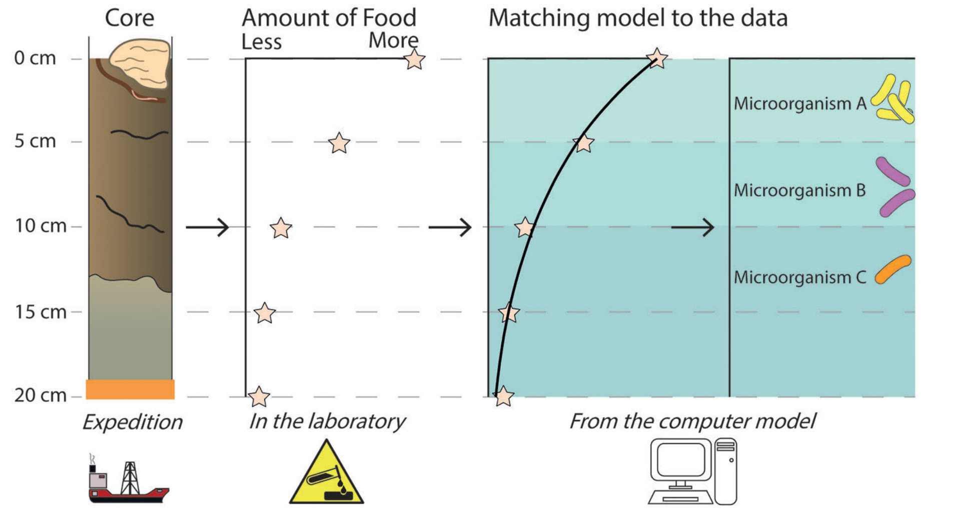

Figure 3

Figure 3

A sediment core is collected, complete with worms and sponges! A chosen condition, such as the amount of food (organic matter) available for microorganisms, is measured in the laboratory. The amount of food decreases deeper into the core because it is being used up by these microorganisms. By using our model and adjusting it until it matches the data, we can find out which microorganisms are multiplying and feasting at each level and how quickly they are doing so. Each of these microorganisms will do slightly different things. For example, they all eat the same food, but they use different chemicals to break the food down during respiration. Because of this, each microorganism is important for influencing what happens to different chemicals in the seafloor. Computer models allow us to learn even more from the information we collected from the expedition and in the lab.

might alter the seafloor, we need to know which processes are actually happening at the places we visit and how important those processes are. This is why computer models are so helpful.

WHAT IS A COMPUTER MODEL?

A model is just a pretend version of the real world, like a computer game. Models include everything from the flight simulators that help to train pilots, to weather forecasting for TV news. They can exist as simple drawings on a piece of paper, to more complicated forms built with computer code. All models are simplified versions of the real world. They are built on what we know about the world, so they can become more complicated the more we understand about different processes that happen in real life. Unfortunately, more complicated models require more powerful and expensive computers to do the calculations. The set-up of complicated models also requires more observations from the real world, which are not always available. So, when we create computer models, we have to be careful about what we choose to include in the models, because we want to be able to get results quickly but not be too simplistic. For example, really fancy game graphics that show exactly what someone or someplace looks like will need your computer to work much harder than if the people were represented as stick figures and the buildings as plain gray blocks!

In the case of the seafloor, we can use a model called the Biogeochemical Reaction Network Simulator (BRNS) [3, 4]. BRNS has over 40 different chemical reactions and can even simulate things like worms mixing up the mud [5]. However, we only use BRNS for individual cores, not for large areas of the ocean, which means we can look at one location in a lot of detail, but still get our results very quickly with normal computers like you have at home. With BRNS,

BOUNDARY CONDITION

A value we use to define the type of environment we are looking at. It is like an instruction to help the model to produce a virtual core similar to what we have measured in the lab.

MODEL FIT

When the model produces a virtual core that matches nicely with the data we have produced in the lab. We achieve this by carefully adjusting the boundary conditions.

we take the measurements scientists collect during their expeditions and get much more information from them. To do this, we use values known as **boundary conditions**, which tell the model what type of environment we are looking at. For example, for the Arctic, our boundary conditions include cold temperatures and a shallow seafloor, as well as the amounts of chemical compounds we have measured in the cores and ocean water just above them. These values turn a blank model into a virtual seafloor that represents the Arctic, but the model can be modified to represent anywhere in the world, as long as the information is available. We can change these boundary conditions until the virtual sediment core looks the same as the values we measured in the laboratory from our real core. When the virtual and the real core match, we call this a **model fit** (Figure 3). The model then lets us see how different reactions in the seafloor add up to generate our observations from the real world. This is useful, as the more we can understand about what is going on in the seafloor now, the more we can learn how it might change over time, if global warming continues to change the conditions of our planet.

ASKING INTERESTING QUESTIONS

When we have our model fit, we can do whatever we like with our virtual seafloor world without causing any harm to the real environment. We can ask our computer model questions like, "what would happen if all the sea ice in the Arctic melted?" This means we can look at what would happen to the seafloor if the world were different, which is an important step toward understanding what our oceans might look like in the future. Governments need this information when making decisions that might affect climate change. In the Arctic, the melting of sea ice is increasing the area where phytoplankton can grow, so our seafloor microorganisms might have more organic matter delivered to them in the future. We can use our model to test this and see how it might impact the seafloor microorganism communities and what the influence could be on the whole Arctic ecosystem.

CONCLUSIONS

Our world is changing very quickly due to climate change and scientists can use models like BRNS to understand what our planet might look like in the future. Going to the places that are changing most rapidly, like the Arctic, can be very helpful, but it is also very expensive and there is only so much we can measure because of time! Frustratingly, there are some processes we cannot measure directly, even though we might know they are happening. We also cannot time travel and go on expeditions in the future or melt sea ice to see how this would impact the seafloor. This is why modeling is such a powerful tool. However, it is very important to remember that successful modeling relies on large groups of scientists from different backgrounds working together and sharing information from countless hours of expedition and laboratory work, to make sure the model best represents the real world!

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

DANNY, AGE: 8

Danny loves science and engineering. He is very interested in space and computers. His dream is to be a Pokemon scientist, or failing that, an architect, or an engineer designing games consoles. Danny is happiest when he is inventing new ideas and crafting prototypes. He has set his heart on creating the first real life Pokemon, and has already prototyped a cardboard DNA machine to write Pokemon DNA. We hope soon to introduce him to the concept of scientific ethics...

AUTHORS

JAMES WARD

I have always been fascinated by the earth, especially the polar regions. I received my undergraduate degree in Geology from the University of Bristol and decided that studying for a Ph.D. would be an amazing opportunity to turn my interest into something useful for science and the environment! I currently work on seafloor sediments from the Barents Sea, looking at how climate change and sea-ice retreat might impact nutrient cycling. You will either find me in the lab measuring silicon isotopes in pore waters or at my desk trying to model them!
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FELIPE S. FREITAS

I am a post-doctoral researcher at the School of Earth Sciences, University of Bristol, investigating how organic matter deposited onto seafloor is transformed and buried. I use computer modeling in combination with field and laboratory observations to understand what controls organic matter preservation and degradation in marine sediments, as well as the implications of those processes for carbon cycling and Earth's climate.

KATHARINE HENDRY

I am a biogeochemist and oceanographer from the University of Bristol. I started my career in the waters around Antarctica but have moved toward the north and now also work in the subarctic and Arctic. My interests lie in understanding how the essential nutrients that fuel life get into—and move around within—the oceans. I use a combination of novel sampling methods, sensors, and cutting-edge laboratory techniques to understand the key processes that control the chemistry of our polar seas.

SANDRA ARNDT

I am a biogeochemical modeler from Université Libre de Bruxelles in Belgium. My research focuses on the development and application of models that are designed to advance our understanding of how essential nutrients for life move around within the oceans and to shed light on the role of the environment in past, present, and future carbon cycling and climate. I am especially interested in the burial of carbon in marine sediments over time and in different environments, and its impact on global nutrient cycles and climate.

HEALTH
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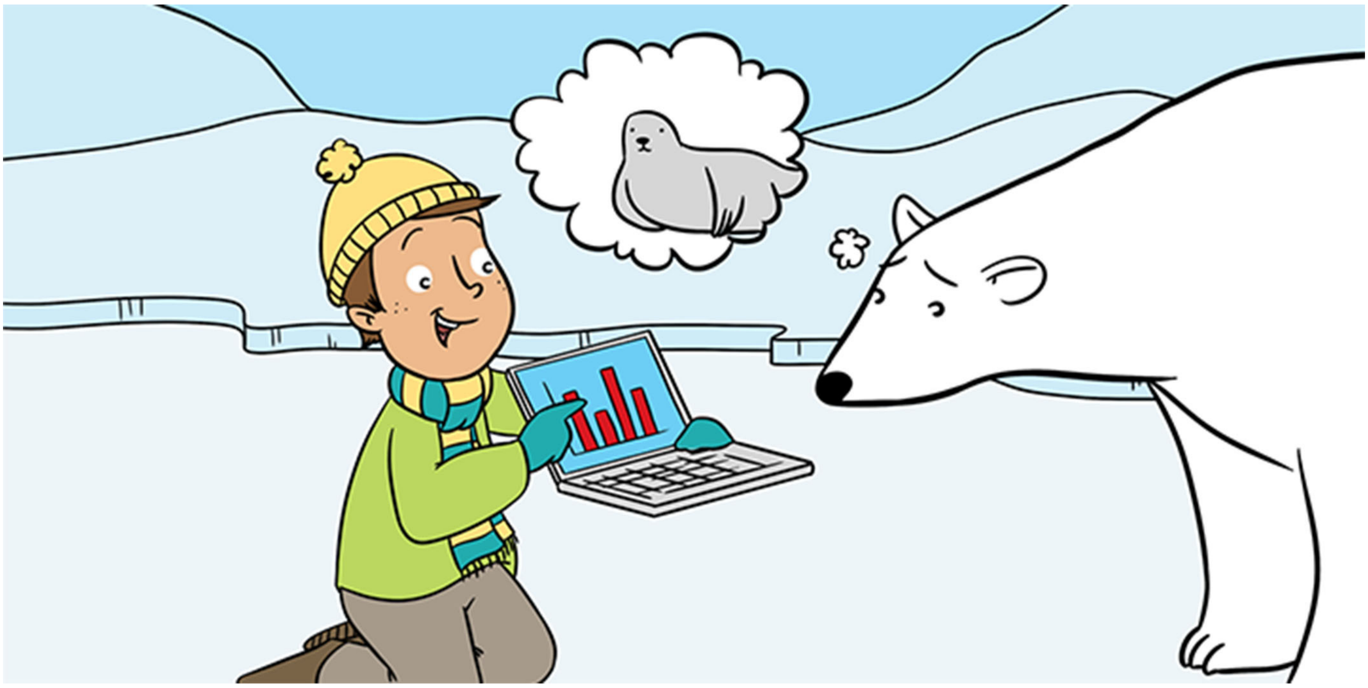

HOW IS CLIMATE CHANGE AFFECTING MARINE LIFE IN THE ARCTIC?

Michael R. Heath [1*], ***Deborah Benkort*** [2], ***Andrew S. Brierley*** [3], ***Ute Daewel*** [2], ***Richard Hofmeister*** [2], ***Jack H. Laverick*** [1], ***Roland Proud*** [3] ***and Douglas C. Speirs*** [1]

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YOUNG REVIEWER:

LILU

AGE: 11

Rising temperatures are melting the ice that covers the Arctic Ocean, allowing sunlight into waters that have been dark for thousands of years. Previously barren ice-covered regions are being transformed into productive seas. In this article, we explain how computer modeling can be used to predict how this transformation will affect the food web that connects plankton to fish and top predators, like whales and polar bears. Images of starving polar bears have become symbolic of the effects of the warming climate. Melting of the sea-ice is expected to reduce the bears' ability to hunt for seals. However, at the same time, the food web upon which bears depend is becoming more productive, so it is not completely clear what the eventual outcome will be. Computer models help us to understand these systems and help us make policy decisions about the management of newly available Arctic resources.

INTRODUCTION

The poles are among the harshest environments on our planet. In the winter, the sun never rises, air temperatures are extremely cold, and snow and ice accumulate. In summer, the sun never sets, it is warmer, and the ice melts back toward the poles. However, there is no doubt that the amount of ice is shrinking as our planet gets warmer. This is happening on the land and at sea. On the land, glaciers are melting and retreating in places like Antarctica, Greenland, and Alaska. At sea, the area of floating ice, which we call **sea-ice**, is becoming smaller each year [1] (Figure 1).

SEA-ICE

Floating ice formed by freezing of the sea surface.

A National Geographic video of a starving polar bear with the caption "This is what climate change looks like" has become an internationally recognizable symbol of the effects of melting sea-ice on the Arctic ecosystem [2, 3]. The story behind the video is that polar bears depend on being able to roam over the ice in search of seals to eat. Because the ice is shrinking they are struggling to find enough food. In this article, we explain why the story may be more complex than it first appears, and how computer models of ecosystems can be used to help us understand these complexities.

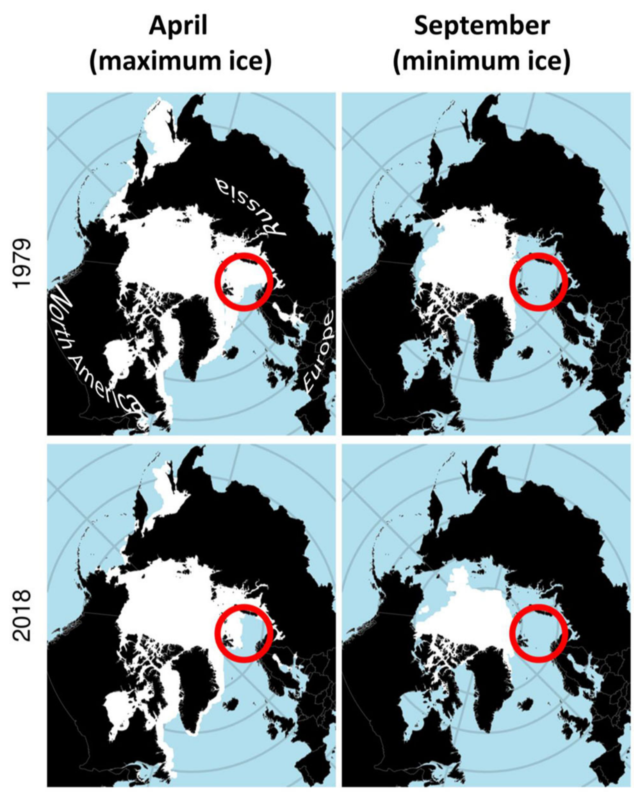

Figure 1

Figure 1

Changes in sea-ice extent (white areas) in the Arctic between 1979 and 2018. On the left, you can see the ice area in April when it is cold and the ice is at a maximum. On the right, you can see the ice area in September when it is warmer and the ice is at a minimum. Each map is centered on the North Pole; land is shown in black, with North America in the lower-left corner, Russia in the top-right, and Europe in the lower-right. The red circle shows the Barents Sea, which is the area that has seen the greatest change in ice cover (source: https://www.ncdc.noaa.gov/snow-and-ice/extent/).

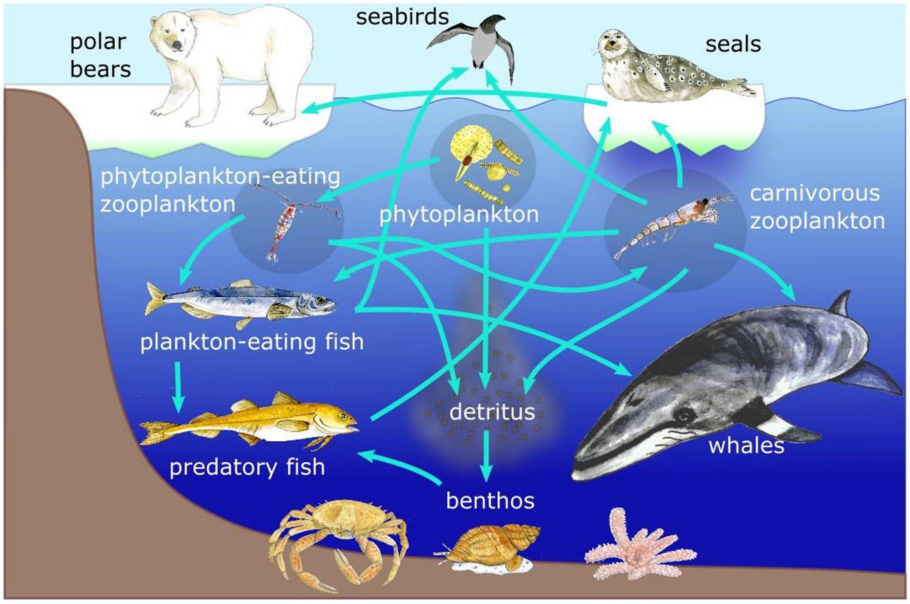

Figure 2

A who-eats-whom food web in the Arctic. The arrows connect each prey group to its predator group (Artwork: Douglas Speirs).

PHOTOSYNTHESIS (FOH-TOH-SIN-THI-SIS)

A chemical reaction in plants and some bacteria. It uses energy from light to convert carbon dioxide and water into organic compounds.

PHYTOPLANKTON (FIE-TOH-PLANGKTUHN)

Microscopic plants cells that drift in the water. There are many species of phytoplankton.

ZOOPLANKTON (ZOHUH-PLANGKTUHN)

A general term for a huge variety of tiny animals that drift in the water.

DETRITUS (DI-TRIE-TUHS)

Remains of dead organisms or waste produced by living organisms.

BENTHOS (BEN-THOS)

A general term for a huge range of animals that live in and on the seabed.

METABOLISM (MUH-TAB-UH-LI-ZUHM)

The combination of chemical reactions required for life.

FOOD WEBS AND ECOSYSTEMS

An ecosystem is a community of bacteria, plants, and animals that occupy the same habitat. All the organisms in an ecosystem are interconnected by a network of who-eats-whom relationships. We call this a food web (Figure 2). Wherever there is sunlight and sufficient nutrients, plants manufacture the materials needed for life in a process called **photosynthesis**. Photosynthesis provides the energy to support all the animals in the rest of the food web.

In the sea, most of the plants are microscopic and we call them **phytoplankton**. Phytoplankton are eaten by a variety of tiny animals up to about the size of a grain of rice, called **zooplankton**. Zooplankton are then eaten by larger zooplankton, jellyfish, and plankton-eating fish, such as capelin. The waste they produce (called **detritus**) is broken down by bacteria as it falls to the seabed, where it provides food for bottom-living animals (called **benthos**). Plankton-eating fish and benthos are food for predatory fish, such as cod and hake, seabirds, and mammals, such as seals and whales. In the Arctic, all these animals are hunted by the top predators, such as polar bears. Humans are also top predators in the food web, because we catch fish and hunt for seals and whales.

HOW IS WARMING OF THE PLANET AFFECTING ARCTIC FOOD WEBS?

Warming has a direct effect on all living organisms. **Metabolism** depends on temperature [4]. Metabolism includes the processes that allow organisms to produce energy from the food that they eat. All organisms have a temperature range in which their metabolism can keep them living comfortably. Tropical species are less tolerant of cold conditions than polar species. This means that, as oceans warm, we expect species found in warm regions to expand their distributions, and we expect those species that prefer colder water to retreat toward the poles. Over the past 50 years, scientists have observed some zooplankton and fish species moving toward the poles, as the oceans become warmer [5].

The effects of warming on the sea-ice are also extremely important for the Arctic food webs. The presence of sea-ice strongly reduces the amount of sunlight that enters the ocean. The shrinking area of sea-ice (Figure 1) means that some parts of the ocean are being exposed to summer sunlight for the first time in many thousands of years. The light enables phytoplankton to grow and photosynthesize in areas that have previously been barren, increasing the productivity of the Arctic.

The increase in phytoplankton could be considered a positive change, leading to more life in the sea and more food for zooplankton, benthos, and eventually fish, birds, seals, whales, and polar bears [6]. However, some of the Arctic species have evolved to depend on the presence of ice. Sea-ice provides a means for seals and walruses to get out of the water. They need to do this to rest, breed, and evade other marine predators, such as killer whales. Other mammals, such as polar bears rely on the ability to travel across the frozen sea to hunt for seals. Melting ice makes travel more difficult because thin ice cannot support the bears' weight. On the other hand, ice is a barrier to whale species because they must be able to reach the air to breathe. Overall, it is not completely clear which of the predators in the food web will be benefited by melting sea-ice and which will be harmed by it.

PREDICTING WHAT WILL HAPPEN IN THE ARCTIC

We use computer models to make predictions about the effects that changes in sea ice will have on food webs. To make these models, we first write down the key processes and components of the food web as mathematical equations. These include feeding, metabolism, photosynthesis, and who-eats-whom. Then we convert the equations into computer code. This gives us a virtual world, in which we can carry out experiments on the model ecosystem. The experiments are designed to help us understand how the ecosystem could change in the future.

We built a simple model of the Barents Sea ecosystem in the Norwegian/Russian Arctic (Figure 1). This model contains data on ice and temperature conditions, and equations to represent some of what we know about the ecosystem's plants and animals. The main simplification is that some species are combined into groups that share similar characteristics, such as size, structure, or diet. For example,

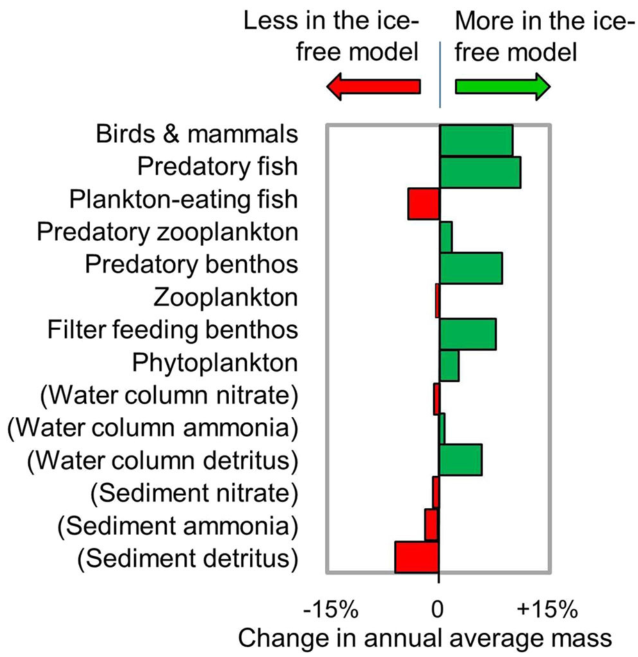

Figure 3

Figure 3

Results from a computer model comparing the mass of different components of the ecosystem (averaged over a year) in a possible future, warmer, ice-free Barents Sea, relative to the present day. Components in brackets are inorganic nutrients or dead material. Green bars to the right show that the quantity of a food web component is greater in the future model than in the present day. Conversely, red bars to the left indicate less mass of those components in the future model.

we combined all birds and mammals into a single group, because they are warm-blooded, which means that they can use energy from their food to maintain a warm body temperature independent of the environment, unlike plankton and most fish. This simplification means that, in our model, we cannot distinguish between polar bears and whales, for example. Although our simplified model is not perfect, it still reproduces the general responses of the natural Barents Sea ecosystem.

The equations in the model include parameters that determine the results. In our model, these include, for example, maximum feeding rates, or sinking rates of detritus. Selecting values for the parameters is an important step in building the model. We try to select values that allow the model to match as closely as possible to the real data from the ecosystem. This ensures that the model is as realistic as possible. Once the model is set up, we can change the ice and temperature conditions to what they might be in the future, and use the model to predict what may happen in real life. In Figure 3, we show an example of a comparison between the present day and future model results. The present-day model represents the Barents Sea as it is today. The future model is ice-free, with water temperatures 0.5°C warmer all year round. As expected, photosynthesis is higher in the future model. The animals that benefit are benthos, predatory fish, and the bird-and-mammal group. Zooplankton and plankton-eating fish are less abundant than they are today. This is because phytoplankton and detritus, upon which the benthos and zooplankton feed, settle to the seabed more quickly when there is no ice. Since we cannot distinguish between different bird and mammal predators in this model, we cannot use it to say exactly which species will be more abundant or less abundant in the future. However, the model predicts that the bird-and-mammal group as a whole will have a diet different from today's, with more feeding on predatory fish and less on planktivorous fish.

WHY DOES ALL THIS MATTER?

The Arctic is warming faster than the rest of the planet. Yearly averaged air temperatures in the Arctic have increased by around 2°C between 1970 and 2010 compared to 0.6°C for the planet as a whole [7]. Summer temperatures in the Canadian Arctic are now higher than at any time in the last 44,000 years [8]. Within the period of a human lifespan, the Arctic Ocean has partially emerged from beneath thousands of years of sea-ice cover.

There is a race between nations to claim the seabed and resources in the Arctic as it emerges from the ice. New routes will become possible for ships to travel between Europe, Asia, and North America. On 30 November 2017, the EU and nine major fishing nations agreed not to develop fisheries in the Arctic Ocean until at least 2033. This is supposed to allow time for scientists to develop the models needed for managing the fish stocks in a sustainable way [9]. There is much research to be completed before we have a full understanding of the effects of warming on the Arctic.

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YOUNG REVIEWER

LILU, AGE: 11
I love polar bears and I am fighting against Climate Change to save them! I love my puppy and guinea pigs too.

AUTHORS

MICHAEL R. HEATH
I am a Professor in the Department of Mathematics and Statistics at the University of Strathclyde, Scotland, and I have been studying marine ecology for about 40 years. My current research interests are the mathematical and statistical modeling of fish populations and fisheries, and the dynamics of ecosystems. *m.heath@strath.ac.uk

DEBORAH BENKORT
I am a scientist at the Helmholtz Zentrum Geesthacht, Germany, working on modeling the chemistry and plankton of the Arctic. During my Ph.D., my research focused on the zooplankton dynamic in the Gulf of St. Lawrence on the Canadian east coast. I developed models to study their growth and reproduction.

ANDREW S. BRIERLEY

I am an ecologist at the Scottish Oceans Institute, University of St. Andrews, Scotland. I have been studying polar seas since the 1990s. I specialize in using echo-sounders to study zooplankton and fish. However, I am presently working in Lake Victoria, East Africa. This is a long way from the Arctic, but lake ecosystems are governed by the same sorts of food-webs that we find in the sea so there is a common thread to my research.

UTE DAEWEL

I am a scientist at the Helmholtz-Zentrum Geesthacht, Germany. I am focused on investigating how physics affects the biology of different types of organisms in the sea. I am doing this by developing mathematical models. One major purpose of my recent research is to understand changes in the marine food web.

RICHARD HOFMEISTER

I received my Ph.D. in physical oceanography at the University of Rostock in Germany. My research at the Helmholtz-Zentrum Geesthacht and the University of Hamburg focuses on modeling of ocean currents to determine how plankton are transported in the seas.

JACK H. LAVERICK

I have a Ph.D. in environmental research from the University of Oxford, where I studied coral ecosystems in Honduras. I used a mixture of machine learning and modeling to investigate changing community structure across depth gradients. Currently, I am a post-doctoral researcher at the University of Stathclyde, Scotland.

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I am a post-doctoral research fellow at the Scottish Oceans Institute, University of St. Andrews, Scotland. I have a Ph.D. in Marine Ecology, M.Phys. in Physics and Astrophysics and an M.Res. in ecosystem-based management of marine systems. I am carrying out research on the ecology and biology of zooplankton and micronekton that live in the open ocean.

DOUGLAS C. SPEIRS

I am a Senior Lecturer in the Department of Mathematics and Statistics at the University of Strathclyde, Scotland. My research involves developing computationally efficient population models of zooplankton and fish stocks. These models have detailed representations of biology, including the growth of individuals as they age, and the way their populations move across the ocean.

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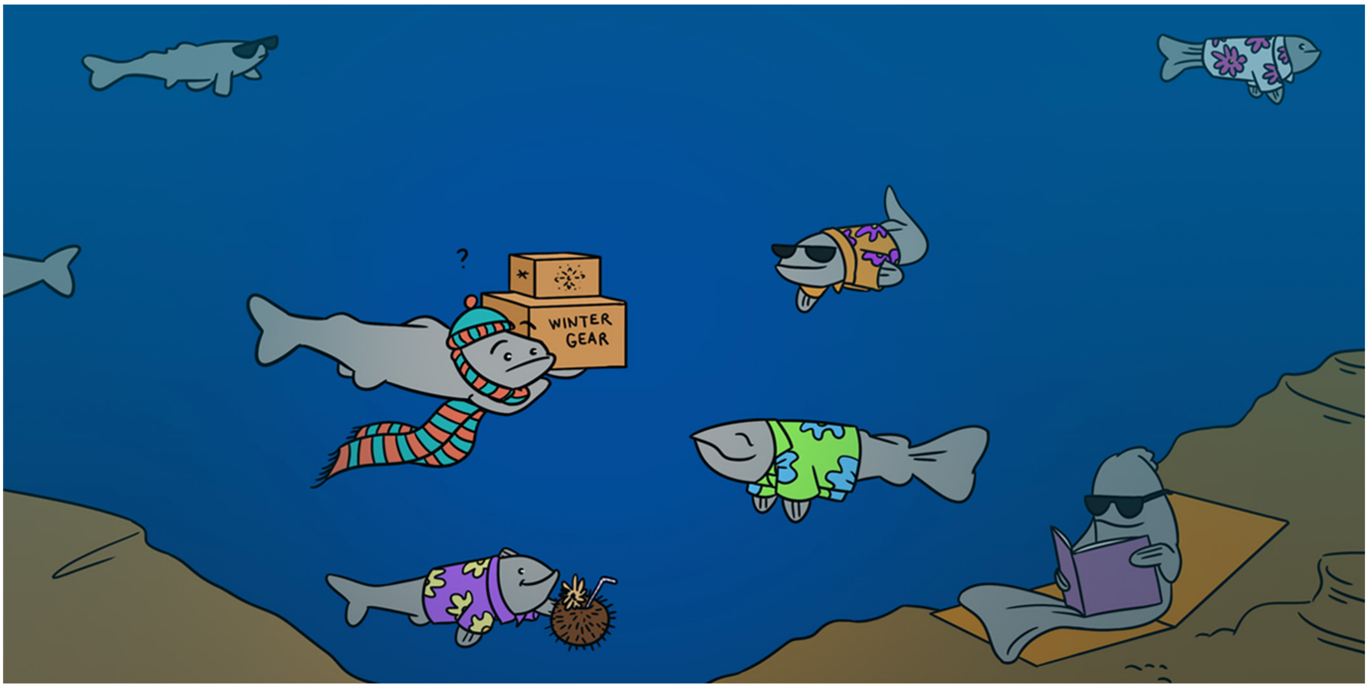

THE POLAR SEA ICE MELTS: WHAT HAPPENS TO THE FISH UNDER THE ICE?

Leif Christian Stige *

Department of Biosciences, Centre for Ecological and Evolutionary Synthesis, University of Oslo, Oslo, Norway

YOUNG REVIEWER:

VARDHAN
AGE: 9

Imagine you are a fish, a polar cod, living in the ocean about halfway between Norway and the North Pole. In the old days, there used to be ice on the sea all winter. In summer, the ice melted. The melting of the ice marked the start of a hectic period with 24 h of daylight, plenty of food, and good conditions for building up your body fat reserves. In late fall, the sea surface froze again, very little light reached the sea, and it was time to rest and live on the fat reserves acquired during summer. In recent years, the sea water temperatures have risen, and a lot of the sea ice has melted. How have these changes influenced the polar cod and other creatures living in the oceans far north?

THE POLAR COD—A TRUE ICE BATHER

Did you know that sea water can be colder than 0°C (32°F) without freezing? While freshwater freezes at 0°C, the salt in the sea water prevents the sea water from freezing until it reaches about −2°C. Fish that swim in such cold waters may, however, freeze and die. Only very hardy fish species can live in this environment. **Polar cod** (called Arctic

POLAR COD

A small fish species that lives in sea areas around the Arctic.

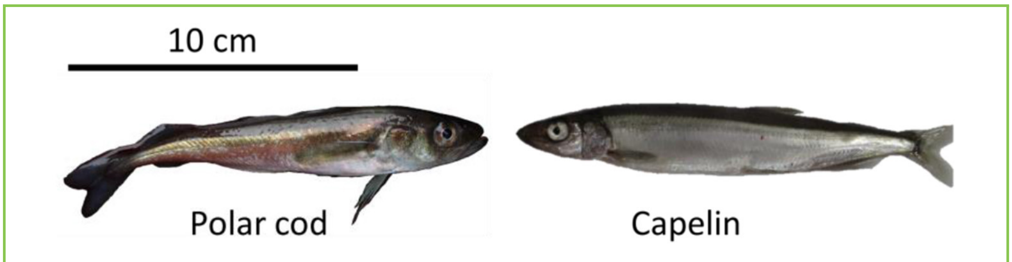

Figure 1

Polar cod and its competitor, capelin. The line shows the scale (10 cm is ~4 inches). Photo: Leif Chr. Stige.

cod in America) is one such hardy species (Figure 1). Polar cod is a relative of the better-known cod that you may have heard of or even eaten, but is a different species. To handle the cold, the polar cod have anti-freeze chemicals in their blood, similar to the way people in cold countries pour anti-freeze into their car engines in winter. The warmer-water relatives of polar cod have no such anti-freeze chemicals, so they wisely avoid very cold waters.

WHICH OCEAN AREAS ARE WE TALKING ABOUT?

Polar cod is one of the most numerous fish species in the northern Barents Sea [1]. The Barents Sea is part of the Arctic Ocean, which is the sea area north of Europe, Asia, and America, with the North Pole at its center (Figure 2). Sea ice covers the central parts of the Arctic Ocean all year-round. In areas farther south, the sea ice melts in summer and freezes again in fall. Even farther south, there is no sea ice at all. In recent decades, the temperatures on earth have risen due to human activities. As a result, much of the sea ice in the Arctic Ocean has melted. Many areas that were previously ice-covered year-round are now ice-free in summer, and many areas that were previously ice-covered in winter and ice-free in summer are now ice-free year-round [2]. One area where these changes are taking place is the Barents Sea.

WHAT DID WE STUDY?

The Barents Sea is the home of large populations of fish, seals, and other animals. Many fishing boats fish in the Barents Sea. Also, scientists regularly go into the Barents Sea on research ships, to find out how many fish are there and how many fish can be harvested by fishermen without depleting the populations. The research ships go on zig-zag routes across the ocean and count the fish along the way, using different kinds of fish-catching and fish-sensing equipment. The scientists calculate the total number of fish by assuming that fish occur in similar numbers between the zigzag tracks as along those tracks. The scientists also assess the living conditions of the fish: the temperature of the water, how much ice there is, and how many animals there are for the fish to eat (the fishes' **prey**).

PREY

An organism that is killed and eaten by a predator.

Figure 2

Figure 2

The location of the Barents Sea.

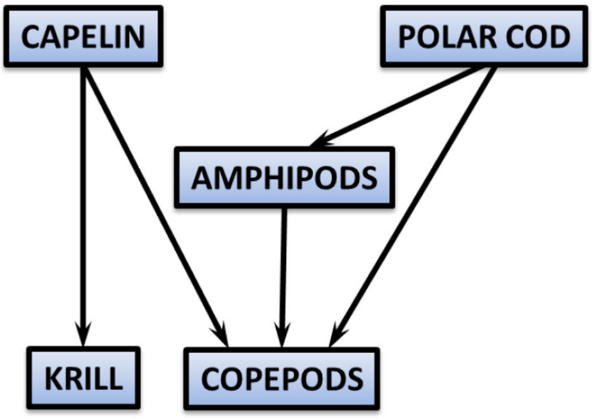

Figure 3

Figure 3

Who eats whom in the northern Barents Sea? A simplified food web of the Barents Sea, with arrows pointing from the key predators (those who eat), in this case capelin and polar cod, to their prey (those who are eaten).

In a recent study, we analyzed some of these data, from the 1980s until now, to investigate how the changes in sea ice have affected the fish and their prey. Over this timespan, there have been many years with little sea ice, many years with lots of sea ice, and many years with intermediate amounts of sea ice. In our study, we compared how the numbers of individuals of different species of fish and their prey changed from 1 year to the next, depending on sea ice conditions and the numbers of individuals of each of the species (Figure 3 shows the food web of the organisms we studied).

WHAT MAY HAPPEN TO THE POLAR COD IF THE SEA ICE DISAPPEARS?

PREDATOR

An animal that kills and eats individuals of other species.

The young polar cod like to swim just under the ice and hide in crevices in the ice if their **predators** come along. The predators are animals that like to eat polar cod, and include other fish species, seals, and sea birds.

Polar cod, in turn, are predators of smaller animals, which we will come back to soon. What happens when the ice disappears? The young polar cod will have nowhere to hide from predators. There may also be more predators around, as higher temperatures allow less-hardy fish species to move in from the south—fish species that like to eat polar cod. On the other hand, decreased amounts of sea ice can also be good for the polar cod, because the spring arrives earlier and the polar cod have more time to swim around, eat, and build up body fat reserves for the winter. It is not obvious if the good effects or the bad effects of decreased sea ice are strongest. We were therefore curious whether the numbers of polar cod tended to increase or decrease in years with little sea ice. But, before revealing what we found for polar cod, let us consider some of its competitors and prey.

THE CAPELIN—A LONG-DISTANCE MIGRANT

CAPELIN

Another small fish species that competes with polar cod for food.

Another fish species that visits the northern Barents Sea each summer is **capelin** [1, 3]. In winter, the capelin swim to areas a bit farther south, where waters are not quite as cold as in the northern Barents Sea and the sea surface does not freeze. In summer, the capelin follow the retreating ice edge northwards, feeding on the plentiful prey organisms found in the waters where the sea ice has recently retreated. Capelin eat many of the same prey organisms that polar cod eat; capelin and polar cod are therefore competitors [4].

KRILL

Small shrimp-like animals with many legs. A key prey of capelin.

We found that the capelin population tended to grow in warm years with little sea ice, possibly because their feeding area was larger during these years. The ups and downs in the capelin population did not depend only on sea ice. It also depended on the numbers of prey and predators: not surprisingly, the capelin population increased the most in years with few predators and many prey. The main predator affecting the capelin was the cod (not the polar cod, but the relative without anti-freeze chemicals). The main prey affecting the capelin was **krill**.

KRILL—"MINI-SHRIMPS"

Krill look somewhat like miniature shrimps. Both krill and shrimps belong to a group of organisms called crustaceans, which have a hard shell and many legs. Krill have ten legs, which they use for swimming. Most krill species do not like very cold temperatures, and there are fewer krill in the northern Barents Sea than in the warmer waters to the south. In years with little sea ice, we found that the number of krill tended to increase in the northern Barents Sea, most likely because they drifted with the currents from the areas farther south.

For the krill, the benefit of a warm year with little sea ice appeared to be only short-term. As you may remember, the number of capelin also increased in warm years with little sea ice, and capelin eat krill. Hence, more krill were eaten by capelin for several years after a year with little sea ice, because there were more capelin around. In other words, the short-term effect of little sea ice on krill in the northern Barents Sea was good, but the long-term effect was bad.

WHAT HAPPENED TO OTHER PREY ORGANISMS?

We also looked into what happened to other small crustaceans that are prey of polar cod and capelin. In short, the main prey of polar cod were reduced in numbers during warm years with little sea ice.

BACK TO THE POLAR COD

To our surprise, we found no association between the ups and downs in the polar cod population and the sea ice conditions. The changes in the polar cod population also showed no relation to the numbers of polar cod's prey and predators. We therefore found no evidence for effects of sea ice on polar cod. This lack of association may mean that, so far, the polar cod has been tough enough to withstand the changes in sea ice, and that other factors besides the amount of sea ice have been more important for driving the changes in the polar cod population. Perhaps, so far, the good and bad effects of decreasing sea ice have canceled each other out? We do not know, and we plan to investigate this question in more detail in future studies.

WHY ARE THESE FINDINGS IMPORTANT?

Understanding how climate influences ecosystems is important for protecting species that are threatened by climate change and for adjusting human activities, such as fishing. For example, fish populations that grow and survive better in a warmer climate may tolerate more fishing in the future than today. Other fish populations may tolerate less fishing and become over depleted unless we reduce the fishing pressure.

By investigating the changes in all these species, we separated the direct and the indirect effects of sea ice changes on each species. By direct effects, we here mean the short-term effects, such as how a decreased amount of sea ice was good for krill in the short term because more krill drifted in from the south. By indirect effects, we mean the longer-term effects that happen through other species, such as how a decreased amount of sea ice was bad for the krill in the long-term, because the number of capelin increased. In fact, we found that the indirect effects were just as important as the direct effects. A take-home lesson from our study is that the indirect effects of climate change through other species may be just as important or even more important than the direct effects on species, such as polar cod.

The long-term fate of the polar cod in a warmer climate remains uncertain. The polar cod probably need sea ice to protect their young, which may force them to move northwards as the ocean temperature rises [5]. Whether the polar cod will thrive in the areas farther north depends not only on the sea ice, but also on what happens to their prey, competitors, and predators. By understanding these relationships, our research can help to protect the polar cod, and possibly other fish species, as the earth's climate continues to change.

ACKNOWLEDGMENTS

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ORIGINAL SOURCE ARTICLE

Stige, L. C., Eriksen, E., Dalpadado, D., and Ono, K. 2019. Direct and indirect effects of sea ice cover on major zooplankton groups and planktivorous fishes in the Barents Sea. *ICES J. Mar. Sci.* 76:i24–36. doi: 10.1093/icesjms/fsz063

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YOUNG REVIEWER

VARDHAN, AGE: 9
My name is Vardhan and I am 8 years old. I enjoy cricket and reading books on outer space. My favorite subjects are Math and English.

AUTHOR

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Leif Christian Stige has worked as researcher at the University of Oslo in Norway for more than 10 years. He investigates how changes in climate and human activities, such as fishing influence marine species. To do so, he analyses data collected over many years, to search for associations between changes in the fish populations and factors, such as climate conditions, other species, and fishing. He is also interested in how oil spills may affect the species in the ocean. Most of his research has been on the Barents Sea ecosystem. *l.c.stige@ibv.uio.no

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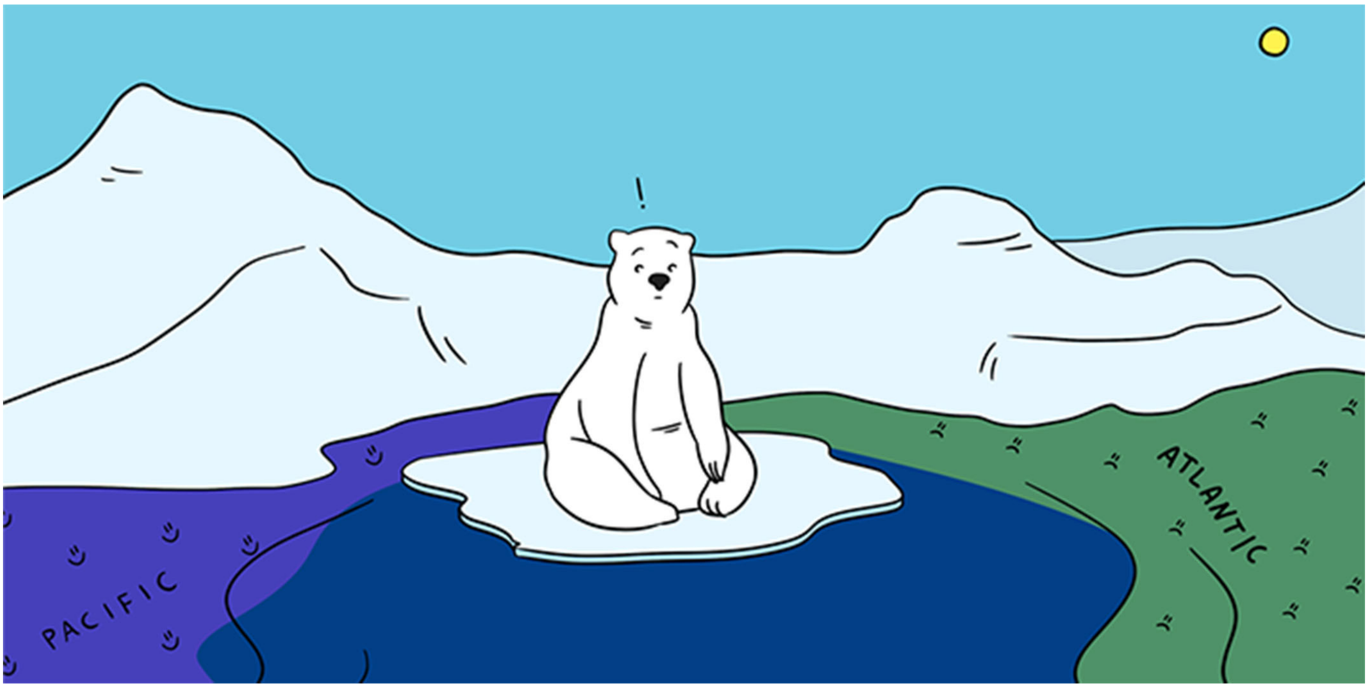

HOW NUTRITIOUS WILL THE FUTURE ARCTIC OCEAN BE?

Pearse J. Buchanan[1*], *Robyn E. Tuerena*[2], *Alessandro Tagliabue*[1] *and Claire Mahaffey*[1]

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YOUNG REVIEWER:

SASYAK
AGE: 12

The ocean seems the same everywhere, whether at your local beach or in the cold Arctic. But ocean properties vary greatly. Like different types of soil on land, some seawater is rich in nutrients, while others are nutrient-poor. If more nutrients are available, then more life can grow. With more life, the ocean can remove more carbon dioxide from the atmosphere and produce more fish for us to eat. Today, climate change is altering the amount of nutrients in Arctic seawater. Nutrient-rich seawater from the Pacific Ocean is flowing more quickly into the Arctic, while nutrient-poor seawater from the Atlantic Ocean is also invading. Which kind of seawater will dominate in a warmer, ice-free Arctic? Will the Arctic become rich with nutrients and support productive ecosystems, or will it become an oceanic desert? Scientists are working hard to predict what will happen in a warmer world.

CLIMATE CHANGE AND THE ARCTIC OCEAN

Earth's climate is changing. The atmosphere and the ocean are warming as humans pump carbon dioxide (CO_2) and other **greenhouse gases** into the atmosphere [1]. The Arctic Ocean is experiencing the most extreme change, with twice the rate of warming than the global average, rapid sea ice loss, and shifting ocean currents. We know that these changes will affect Arctic ecosystems, but how exactly? Unfortunately, scientists are still unsure how Arctic marine ecosystems will change. One of the major uncertainties comes from our inability to predict what will happen to the nutrients dissolved in Arctic seawater.

GREENHOUSE GAS

A gas that contributes to the warming of the earth known as the greenhouse effect by holding heat within the earth's atmosphere.

WHY SHOULD WE CARE ABOUT NUTRIENTS?

Just like soils that allow the vegetables you eat to grow, seawater has nutrients that allow **phytoplankton** to grow. Phytoplankton are tiny, microscopic plants that live in the **euphotic zone** (the sunlit surface ocean). Phytoplankton need light and nutrients to live. A nutritious ocean is one that has enough nutrients to support a **productive** phytoplankton community, one with an abundance of fast-growing phytoplankton.

PHYTOPLANKTON

Tiny marine algae that form the base of marine food webs.

EUPHOTIC ZONE

The upper part of the Ocean where sunlight is available.

PRODUCTIVE

The ability to produce large amounts of something. Regarding phytoplankton, "productive" refers to high concentrations of these organisms in a given area.

Phytoplankton are vital for marine food webs. If enough nutrients are available for phytoplankton, these microscopic plants can support a diversity of marine animals. Productive phytoplankton communities therefore support the fisheries that almost 1 billion people rely on for food every day.

Phytoplankton also cool the planet by absorbing CO_2 as they grow and perform **photosynthesis**, drawing this greenhouse gas out of the atmosphere and into the ocean. When phytoplankton die, the CO_2 they absorbed then sinks into the deep ocean and may be buried in sediments [1]. Nutritious regions of the ocean that support productive phytoplankton communities may therefore draw CO_2 out of the atmosphere, helping to cool the rapidly warming planet.

PHOTOSYNTHESIS

The process of converting sunlight and carbon dioxide (CO_2) to chemical energy in the form of sugars and other carbohydrates, so that plants can grow.

This is why we care about nutrients. By supporting productive phytoplankton communities, nutrients are important for ecosystems, fisheries, and the climate.

IS THE ARCTIC A NUTRITIOUS OCEAN?

Not all seawater is equal. In some regions of the ocean, despite receiving plenty of light for photosynthesis, nutrients are low and life is scarce. In other regions, nutrients are rich and marine life is bountiful.

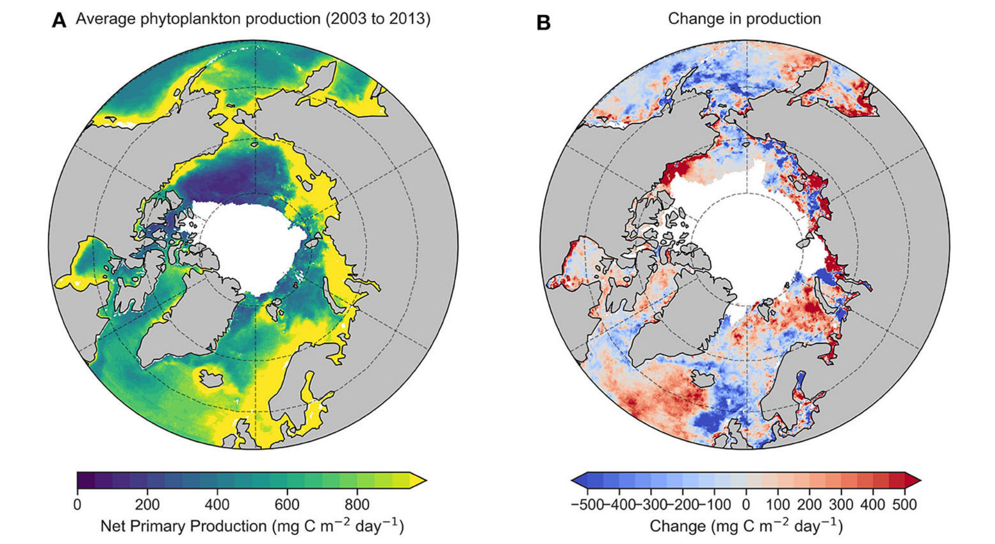

Figure 1

Figure 1

Satellite measurements of phytoplankton production in the Arctic Ocean. **(A)** Average phytoplankton production between the years 2003 to 2013, with highly productive areas in green and yellow. You can see that many places in the Arctic Ocean are productive. **(B)** The change in phytoplankton production between a warm year (2012) and a cold year (2003). While there is a lot of patchiness, increases in phytoplankton production (red colors) are common around the edge of the sea ice (white area), which is melting rapidly and increasing the amount of light available for phytoplankton. You can also see that area of sea ice (white area) is smaller in **(A)** than in **(B)** because of sea ice loss since 2003.

PIGMENTS

The natural coloring matter of tissue, in this case the compounds within phytoplankton cells that absorb certain wavelengths of light for photosynthesis.

We can observe these “deserts” and “gardens” of the ocean using satellites, which can detect how productive phytoplankton are, all over the world. Satellites do this by measuring slight changes in the color of light that is reflected off the ocean [2]. Phytoplankton have unique **pigments** inside their cells that are used in photosynthesis. These pigments alter the color of light that reflects off the ocean and bounces back into space, which allows satellites to detect changes in phytoplankton. Satellite studies of the Arctic have shown that, overall, the Arctic Ocean is productive in many regions (Figure 1A), which means the Arctic waters are nutritious.

RECENT CHANGES

There is a strong possibility that the Arctic will become more productive as it warms up. As sea ice melts, more light becomes available to fuel phytoplankton growth. With more phytoplankton, the Arctic could support more fish. It could also absorb more CO_2, possibly helping to draw some CO_2 out of the rapidly warming atmosphere.

In fact, Arctic phytoplankton production has increased by 30% over the last few decades, with large increases where sea ice loss has been most extreme [3] (Figure 1B). However, scientists do not know if the increase in phytoplankton production will continue. The evolution of Arctic phytoplankton production will depend on whether its seawater remains nutritious. To predict how nutritious a future Arctic will be, we must understand how the Arctic receives its nutrients. To do that, we must leave the Arctic.

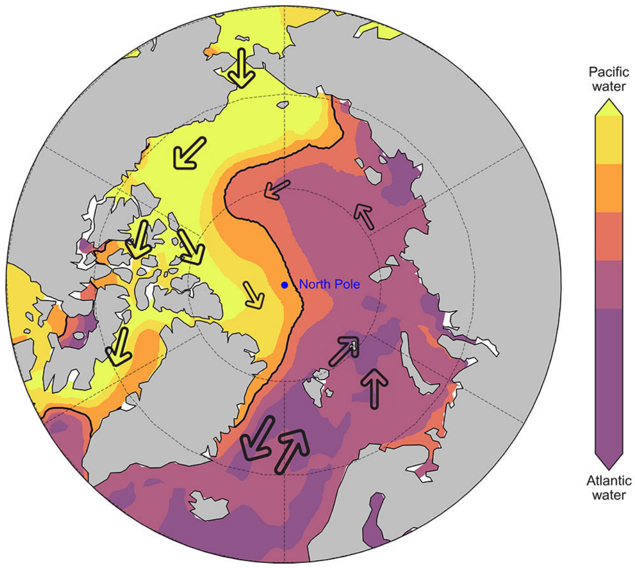

Figure 2

Figure 2

Pacific seawater (yellow) and Atlantic seawater (purple) dominate certain areas of the Arctic Ocean. You can see the boundary between Pacific and Atlantic seawater by the solid black line. Pacific seawater is highly nutritious compared with Atlantic seawater, so you can think about the areas in yellow as being rich in nutrients. Arrows indicate the basic circulation pattern, as determined by an ocean model simulation.

THE ARCTIC'S OCEANIC PARTNERS: THE PACIFIC AND THE ATLANTIC

Even though the Arctic is small, it is an important meeting place of two larger oceans: the Pacific and Atlantic (Figure 2).

The Arctic receives Pacific seawater through the Bering Strait, which is the small, shallow opening between Alaska and Russia. Meanwhile, Atlantic seawater flows into the Arctic between Greenland and Scandinavia. Pacific seawater dominates the western Arctic near Canada, while Atlantic seawater dominates the east near Europe and Russia.

Distinguishing between the Pacific and Atlantic inflows is important because the nutrient content of Pacific and Atlantic seawater differs considerably. Pacific seawater is nutrient-rich, while Atlantic seawater is nutrient-poor. The relative influence of Pacific or Atlantic seawater in the Arctic therefore determines its nutritiousness, which determines how productive phytoplankton can be.

ALONG COMES CLIMATE CHANGE: A BATTLE BETWEEN THE PACIFIC AND ATLANTIC

Today, more water is moving into the Arctic from both the Pacific and Atlantic Oceans, meaning that more Arctic water is being pushed out [4, 5].

So, what does this mean? First, that the properties of Arctic seawater are changing quickly. The rapidity of change threatens to alter phytoplankton communities, which could affect organisms higher up the food web, including marine mammals, possibly causing a total reorganization of Arctic ecosystems.

Second, we think that the contest between the Pacific and Atlantic will determine the productivity of the phytoplankton that live in the Arctic and, ultimately, the kinds of animals that live there. If the Atlantic influence continues to grow, then the Arctic may be unproductive, even with lots of light as sea ice melts. However, if the Pacific influence grows and exceeds that of the Atlantic, then the Arctic could be more nutritious and productive.

It is important to realize, however, that a possible increase in phytoplankton in the Arctic does not make climate warming a good thing. Climate warming is causing huge change throughout the Earth's biosphere, of which the Arctic is only a small part. Sea-level rise across the world could displace many people from their homes, and some ecosystems may become less productive, particularly in tropical regions. The potential increase in fish abundance and CO_2 uptake in the Arctic is only a small part of a global story.

SO, HOW NUTRITIOUS WILL THE ARCTIC BE IN THE FUTURE?

The short answer is that we still do not know how nutritious the future Arctic will be. Although scientists are using satellites, ships, and computer models to monitor the Arctic Ocean [3–5], it is still difficult to predict what will happen there in the future, due to the complexities of physical and biological systems. This uncertainty makes it difficult to predict the consequences for Arctic ecosystems, its fisheries, and its contribution to reducing atmospheric CO_2.

However, what *is* clear is that the Arctic is changing quickly, and that the nutrients supplied from its oceanic partners, the Pacific and the Atlantic, are becoming more important as sea-ice melts.

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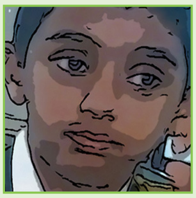
YOUNG REVIEWER



SASYAK, AGE: 12
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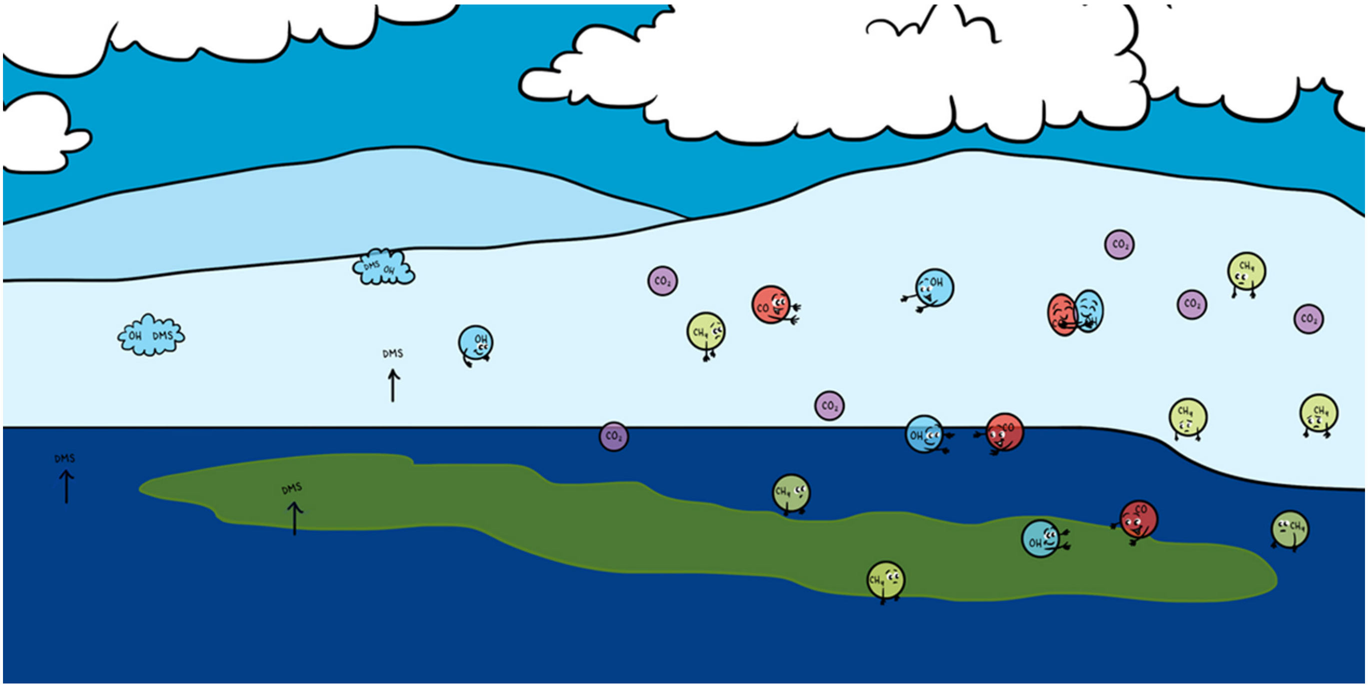

TINY BUT POWERFUL: HOW TINY AMOUNTS OF CERTAIN GASES CAN MAKE A BIG DIFFERENCE IN THE EARTH'S CLIMATE

Hanna Campen and Hermann W. Bange*

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YOUNG REVIEWERS:

FINN
AGE: 11

RUARI
AGE: 12

Comparable to carbon dioxide, dimethyl sulfide (DMS), and carbon monoxide (CO) are tiny gases that have a great impact on our climate. Though occurring only in very small amounts in the atmosphere they are climate influencers, especially in the Arctic. The Arctic is a unique place on Earth where all life is adapted to the extreme cold. Therefore, global warming is a great threat to the Arctic. DMS and CO are produced in the Arctic Ocean and can go into the atmosphere. There, CO may enhance the warming of the Arctic. On the other hand, DMS possibly cools the atmosphere because it helps forming clouds. The processes CO and DMS are involved in, are complex and will probably alter under a changing climate. It is important to understand these processes to get an idea of the future Arctic Ocean and climate to find ways to save the Arctic.

TINY GASES MAKE A DIFFERENCE!

That sounds funny at first glance but, looking more closely, this is not only true when we are in an elevator realizing someone had beans for lunch. It is also true for so-called **trace gases**. Trace gases occur in our atmosphere in very small amounts. But do not be fooled: they influence Earth's climate in a big way, namely through their behaviors and interactions. This is especially true in the **Arctic Ocean**, one of the most impressive, yet vulnerable, places on Earth. You have probably heard of carbon dioxide, since it is one of the key drivers for climate change—the star influencer among trace gases. But have you heard of **carbon monoxide** and **dimethyl sulfide**? They are further influencers—trace gases whose forces we should not overlook. Here comes their story. Where do they come from? How powerful are they and will they influence the future of the Arctic? On Instagram, we follow influencers and let them affect our behavior. Why do not we take trace gases as an inspiring example, too? Even though we may feel tiny when facing this overwhelming climate problem, our individual behavior makes a difference!

TRACE GASES

Gases that make up together <1% of our atmosphere (Figure 1).

ARCTIC OCEAN

The Arctic Ocean includes the North Pole region and is surrounded by northern parts of Europe and Asia and North America. It is the coldest, smallest and shallowest ocean compared to the Pacific, Atlantic, Indian, and Southern Oceans. Polar bears live in the Arctic region but there are no penguins.

CARBON MONOXIDE

A less known trace gas that has the potential to enhance global warming.

DIMETHYL SULFIDE

A gas that possibly cools the atmosphere by helping to form clouds.

WHAT DO WE MEAN BY TINY?

As the name trace gases indicates, these gases only occur in the air in very small (trace) amounts. You may already know that the air we breathe consists mainly of nitrogen and oxygen, so these are not considered trace gases. All trace gases together make up <1% of the atmosphere. Carbon monoxide and dimethyl sulfide are only two of several trace gases, thus they represent an even tinier fraction (Figure 1). We might conclude that a small fraction means a small impact; so we may think that trace gases are not very important. However, this is not true at all! Carbon dioxide (CO_2) is a trace gas, too. Its properties, in combination with its increasing concentration in the atmosphere, keep the warmth of sunlight trapped close to the Earth longer, so that the Earth warms up. This is similar to the way a greenhouse allows tomatoes to grow, even in wintertime, so we call it the **greenhouse effect**. The greenhouse effect is so strong that it influences the entire world's climate. But what about carbon monoxide and dimethyl sulfide? In the rest of this article, we will explain the influence of these important trace gases on the Earth's climate.

GREENHOUSE EFFECT

The burning of oil and gas releases certain trace gases. Some of those gases are acting as greenhouse gases and accumulate in the atmosphere of the Earth. Like a greenhouse, they keep more warmth of the sunlight in the atmosphere, which leads to global warming.

WHAT IS CARBON MONOXIDE AND WHERE IS IT FOUND?

#Climateinfluencer #Indirectgreenhousegas #Oceanproduct #Interactionlover

Carbon monoxide (CO) mainly occurs where things are burning. You may have heard that CO is a dangerous gas that can be poisonous at certain levels. Most CO comes from the burning of

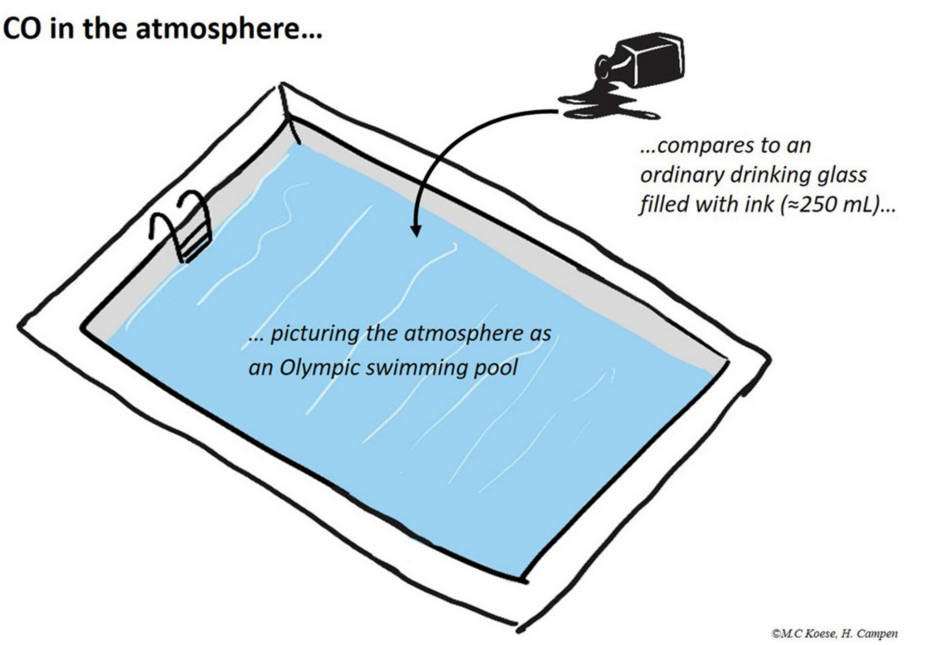

Figure 1

Figure 1

All trace gases together make up <1% of the atmosphere. Carbon monoxide (CO) is one of these trace gases. Picture the atmosphere as an Olympic-size swimming pool. Also picture an ordinary drinking glass filled with ink. Pour this glass of ink into the pool and watch how much it dilutes in the water. That equals approximately the amount of CO in the atmosphere[1].

[1] Volume of an Olympic-size swimming pool: 50 × 25 × 2 m = 2,500 m^3 = 2,500,000 liters. Fraction of CO in the atmosphere: 10^{-7} = 0.0000001. Volume of ink required to obtain the same fraction in the pool: 0.0000001 × 2,500,000 liters = 0.25 liters, i.e., an ordinary drinking glass (250 mL) filled with ink.

fuels, such as petrol. However, scientists found out that the ocean contains a lot of CO, too. In the ocean, floating dead plant material and tiny marine algae, called **phytoplankton**, react with sunlight to produce CO [1]. The amounts of CO produced at certain areas of the ocean's surface can become so large that it goes into the atmosphere. That is why scientists call the ocean a source of atmospheric CO—#oceanproduct.

PHYTOPLANKTON

Tiny, floating marine algae that are the base of all life in the ocean.

How does CO behave in the atmosphere? As you can see from Figure 2, CO is a simple molecule. It consists only of one carbon and one oxygen atom. However, because of its properties, it likes interacting and reacting with other molecules in the air. That is what characterizes its influence -#interactionlover. Once CO is released into the air, its favorite reaction partners are hydroxyl molecules (OH·). This means that OH· is CO's best friend and they love to interact with each other. In their interaction, CO rapidly takes up the oxygen atom of OH·. Hence, that gives CO + O. Any idea what that forms? Exactly: CO_2–a greenhouse gas.

OH· molecules are often called the cleanser of the atmosphere, because OH· can react with and destroy many atmospheric compounds, including some dangerous ones. For example, OH· also reacts with methane (CH_4), another trace gas and a powerful greenhouse gas like CO_2. When OH· reacts with CH_4, the danger of CH_4 is invalidated. However, OH· likes reacting with CO much more. Thus, if CO is present, it takes away OH·, the potential reaction partner of CH_4, and prolongs the time CH_4 stays in the atmosphere [2]. That enhances the harmful warming effect of CH_4 on the atmosphere. So, CO causes a chain reaction that in turn leads to warming. That

Figure 2

(A) Carbon monoxide (CO) and **(B)** dimethyl sulfide (DMS). CO consists of one carbon (pink) and one oxygen (blue) atom bonded to each other. DMS consists of two methyl groups (pink and green) connected by a sulfur atom (yellow) in its center. A methyl group is one carbon atom binding three hydrogen atoms.

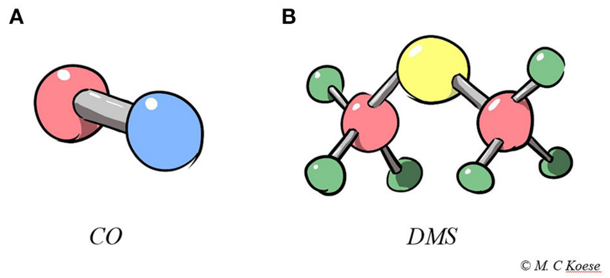

Figure 2

is why CO is called an #indirect greenhouse gas—an influencer of the climate.

At this point, it may be clearer to you why we care how much CO is produced in remote oceanic areas, such as the Arctic Ocean. The Arctic Ocean is less influenced by land-produced CO than many other areas of the world, simply because the surrounding land is not so densely populated. The release of CO from the Arctic Ocean into the atmosphere could make a difference for the Arctic climate. Does this mean there is no good news for the Arctic Ocean? The question is, are there other influencer molecules that might counteract the effect of the CO that is released from the ocean? Now DMS comes into play.

WHAT IS DIMETHYL SULFIDE AND WHERE IS IT FOUND?

#climateinfluencer #sulfurcontainer #cloudcreater #biologicalproduct

Dimethyl sulfide (DMS) is a simple molecule, too. It consists of two methyl groups at its ends and one sulfur atom in its center—#sulfurcontainer. A methyl group is a carbon atom binding three hydrogen atoms. However, the sulfur atom makes the molecule special: sulfur is needed for all living organisms to build proteins and other key components of their cells. In the ocean, DMS is produced by phytoplankton and bacteria [3]—#biologicalproduct. Hence, through DMS production, sulfur becomes available to other organisms. However, like CO, DMS can be released from the ocean into the atmosphere. And there, its sulfur plays another central role!

When released into the atmosphere, DMS can help to create clouds. Once DMS is in the air, it also reacts with OH· and makes cloud-forming particles called cloud condensation nuclei. You can picture a **cloud condensation nucleus** (CCN) as a very small particle that acts like a seed—a seed for a cloud that will grow around it—#cloudcreater. You have probably noticed that the more clouds there are in the sky, the less sunlight reaches us on the ground. The clouds reflect the sunlight back to space, and less sunlight at

CLOUD CONDENSATION NUCLEUS

A particle in the air that acts like a seed for cloud formation. Around it a cloud can grow.

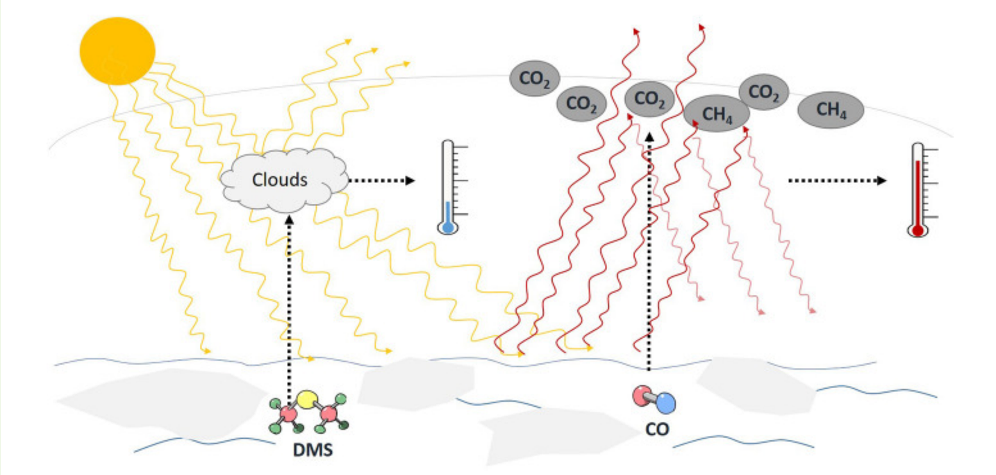

Figure 3

Figure 3

All trace gases together make up <1% of the atmosphere. CO and DMS are two of these trace gases. DMS can help to create clouds, which could potentially lead to a cooling of the atmosphere. CO could further warm the atmosphere because it promotes the formation of further greenhouse gases, such as CO_2, and prolongs the lifetime of CH_4 in the atmosphere. So, it is difficult to predict what the overall influence of trace gases on the Arctic climate will be in the future.

the Earth's surface means the surface gets cooler. Scientists call this cloud formation theory the CLAW hypothesis, which is summarized as follows: marine phytoplankton can cool the Earth by producing DMS, and consequently, clouds [4] —#climateinfluencer. It is crucial that we find out if the CLAW theory is true for remote areas, like the Arctic Ocean, which are especially threatened by warming. That is why we want to study DMS production and all related processes very carefully in the Arctic Ocean.

WHY IS THE ARCTIC OCEAN SO IMPORTANT?

Cooler areas of the Earth can warm faster than areas that are already relatively warm. Scientists have seen that the Arctic region, therefore, is warming much faster than other regions of the world. This is important because the Arctic region plays an important role in global weather and climate. The Gulf Stream is a good example of the Arctic's influence. The Gulf Stream is an ocean current that brings warmth from the tropics to Europe and is thus responsible for the mild climate in Europe. The Gulf Stream's main driving force is seawater from the Arctic, which is very cold and salty. Cold, salty seawater is so heavy and dense that it sinks down to the ocean bottom, resulting in major water movement, kind of like a pump. Now imagine that the Arctic Ocean's temperature and salt content change. The melting of Arctic ice due to the ongoing warming of the Arctic will add loads of fresh water, which contains less salt than seawater. This warmer, fresher water will not sink like cold, salty water, and this change could weaken the Gulf Stream. Changes to the Gulf Stream would not only affect the Arctic itself, but could have consequences for other places in the world too, such as Europe.

So, you can see that it makes sense to investigate the many consequences of climate change in the Arctic, to learn from them, and to determine how these changes might affect other areas of Earth. Moreover, we need this information to predict how weather and climate will behave in the future—how our world will look when you are 90. By predicting the future climate, we can hopefully find ways to adapt to the changes or even find solutions to stop them.

HOW WILL CO AND DMS INFLUENCE THE FUTURE OF THE ARCTIC OCEAN AND OUR CLIMATE?

We all know that the Earth is getting warmer, especially the Arctic Ocean. Thinking of the interactions we have just discussed, the picture becomes clear: environmental changes like climate warming and melting ice can affect the production and release of CO and DMS in the Arctic Ocean [5, 6]. However, we also saw how complex the production and release processes of DMS and CO are. That is why we are uncertain whether CO and DMS in the Arctic Ocean will become more or less abundant and, in turn, whether that would cool or further warm the Arctic atmosphere (Figure 3).

Finally, we explained that what happens in the Arctic Ocean does not necessarily stay in the Arctic Ocean, but these changes can affect the rest of the world's climate. Therefore, it is extremely important to continue to investigate the behavior of climate-relevant trace gases like CO and DMS in the Arctic, under different future scenarios. Even though trace gases occur in tiny amounts, they still make a big difference.

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YOUNG REVIEWERS

FINN, AGE: 11

My name is Finn and I am 11 years old. My hobbies are running, reading (including this paper!), drawing, football, cooking, and sleeping! I also love swimming, which is really fun, especially butterfly. We go on many holidays together as a family and my favorite ones so far were going to Japan and hiking from hut to hut in the Pyrenees. At school, I like maths the most and in my opinion, it is the easiest subject.

RUARI, AGE: 12

Ruari loves science, particularly anything related to space! He hopes to be an astronaut 1 day and really wants to travel to Mars. He loves reading adventure books, doing back-flips on his trampoline and playing the pipes, when not at school.

AUTHORS

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Hanna Campen looks on how certain gases occurring only in tiny amounts in the atmosphere influence climate. She investigates how that will evolve in a future changing Arctic Ocean. She studied biology and biological oceanography in Kiel, Germany. Now she is doing her Ph.D. at the GEOMAR Helmholtz Centre for Ocean Research Kiel. She is passionate about seeing nature as our home and therefore protecting it. She thinks that talking about climate change and its consequences with as many people as possible eventually helps to change how we treat our only planet. *hcampen@geomar.de

HERMANN W. BANGE

Hermann Bange studied chemistry in Göttingen and Freiburg. He is now working as a marine biogeochemist at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, Germany. He is an expert for measuring climate-relevant gases, such as nitrous oxide, methane, carbon monoxide, and dimethyl sulfide. Since the time of his Ph.D. he is fascinated by the fact that tiny gases with very low abundances in both the oceans and the atmosphere can make a huge impact on the Earth's climate.

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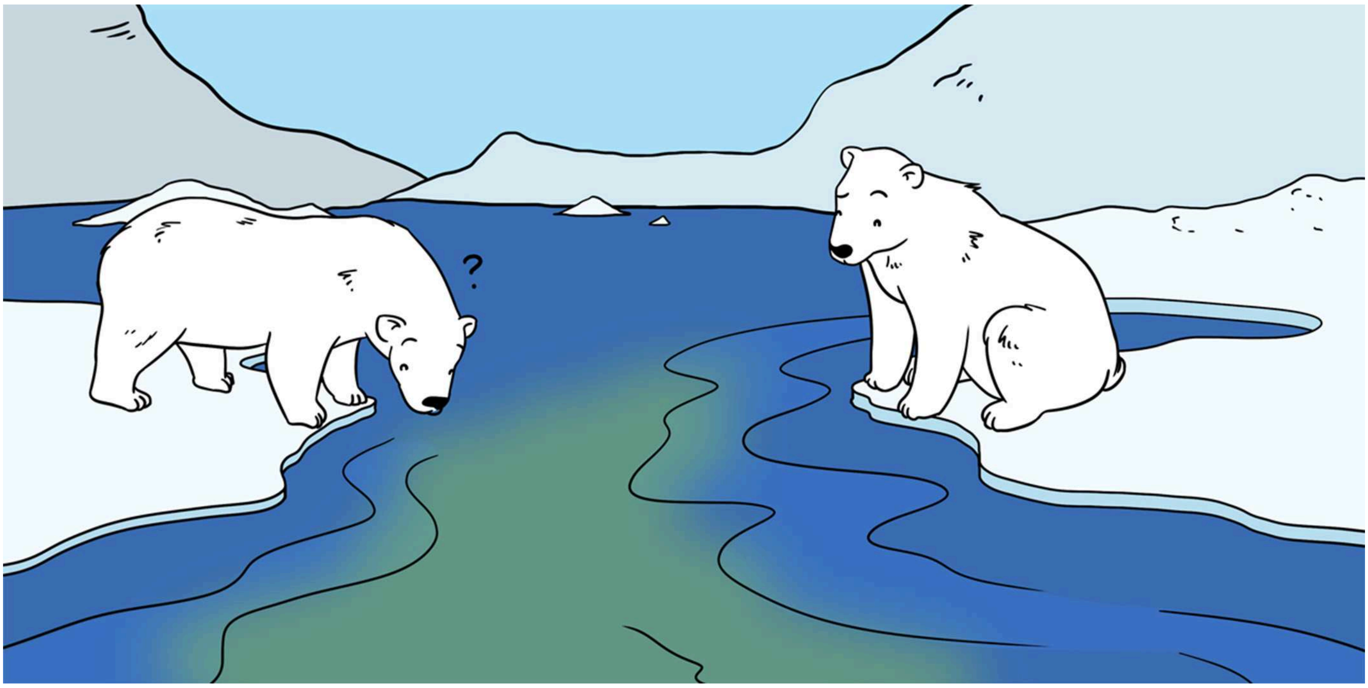

THE CARBON STORY OF A MELTING ARCTIC

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YOUNG REVIEWERS:


CLAIRE
AGE: 15


JULIETTE
AGE: 15

Large parts of the far north of our planet, the Arctic, were permanently covered with ice for thousands of years, but this is now changing. By burning fossil fuels like coal and oil, we rapidly return carbon, stored for millions of years in the Earth's crust, back into the atmosphere. This increases the carbon dioxide (CO_2) concentration in the atmosphere and causes Earth's surface temperature to rise. Warmer temperatures and melting sea ice and glaciers are changing the Arctic environment. In a few decades, the North Pole could be ice-free for the first time in human history. A warming Arctic will have global consequences, through higher sea levels, changes in climate and precipitation patterns, and loss of fish, birds, and marine mammals. In this article, we discuss how large changes in the Arctic environment may affect the entire planet.

POLAR MELTDOWN IN A WARMING WORLD

The Arctic and Antarctic are the Earth's north and south polar regions. They stand out on our planet as hostile, icy deserts with average

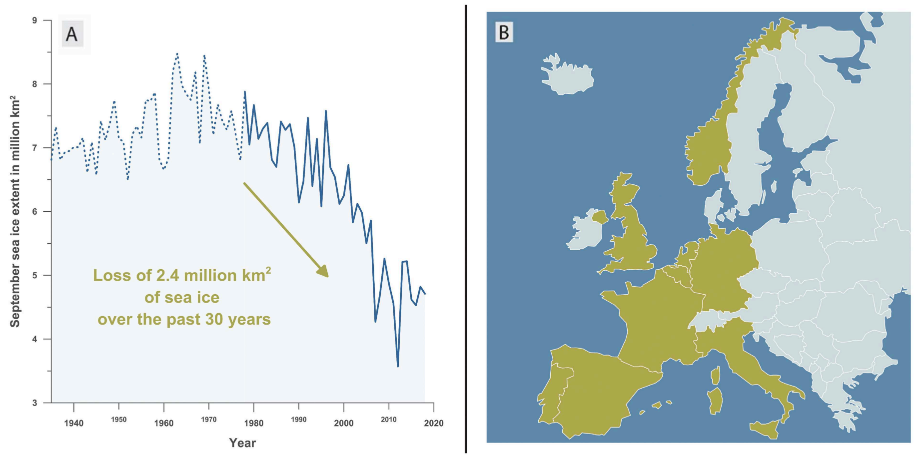

Figure 1

Figure 1

(A) The amount of Arctic sea ice per year (in September) from 1935 to 2018. From 1935 to 1979 (dotted blue line) the ice extent was estimated from atmospheric temperature measurements [1]. From 1979 onwards (solid blue line), the ice extent was measured directly by satellites. You can see that since 1970 almost 40% of the Arctic sea ice has melted. **(B)** The area of all the yellow countries (Portugal, Spain, France, Italy, Belgium, the Netherlands, United Kingdom, Germany, and Norway) is about 2.4 million square kilometers—the same area that has been lost from Arctic sea ice melting over the past 30 years.

winter temperatures of −40°C at the North Pole and −60°C at the South Pole. During winter, the polar regions experience months of complete darkness, while during summer, the sun never sets. Although both polar regions are cold and receive the same amounts of sunlight during the year, there is a fundamental difference between the Arctic and Antarctic.

Antarctica is a continent covered by ice and surrounded by the Southern Ocean. The Arctic is mostly an ocean, covered by sea ice and surrounded by three continents: North America, Asia, and Europe. Current **climate** change is raising Arctic air and ocean temperatures, causing the area covered by sea ice to shrink. During the past 30 years, about 2.4 million square kilometers of Arctic sea ice have melted—this is equivalent to an area the size of western Europe (Figure 1). Although the Arctic is an ocean, the sea ice acts like a land surface, creating an important **habitat** for many animals like seals and polar bears (Figure 2). Since the 1970s, almost 40% of the total Arctic sea ice has disappeared, and the large and small animals that live on that ice are losing their homes and must find other places to live, before they become extinct. On the other hand, certain fish species and algae known as phytoplankton can now thrive in the newly ice-free areas (Figure 2).

CARBON DIOXIDE UPTAKE BY PHYTOPLANKTON

Current climate change is causing Arctic air temperatures to increase about twice as fast as average temperatures over the rest of the world [2]. The rising temperatures in the Arctic region will not only melt sea ice, but will also cause higher amounts of freshwater from melting glaciers to flow into the Arctic Ocean. This freshwater can be rich in **nutrients** that provide essential fuel for phytoplankton growth. Phytoplankton are very important; like plants on land these organisms

CLIMATE

Changes in air temperature, wind speed and direction, precipitation and cloud cover in a time range of hours, days, and weeks is what we call "weather." Climate is the average weather over a longer period of time (decades to millions of years) at a certain location. It is not possible to see, feel, or measure climate.

HABITAT

A habitat is the environment where a plant or animal normally lives and grows.

NUTRIENTS

A nutrient is a chemical substance required by organisms to live.

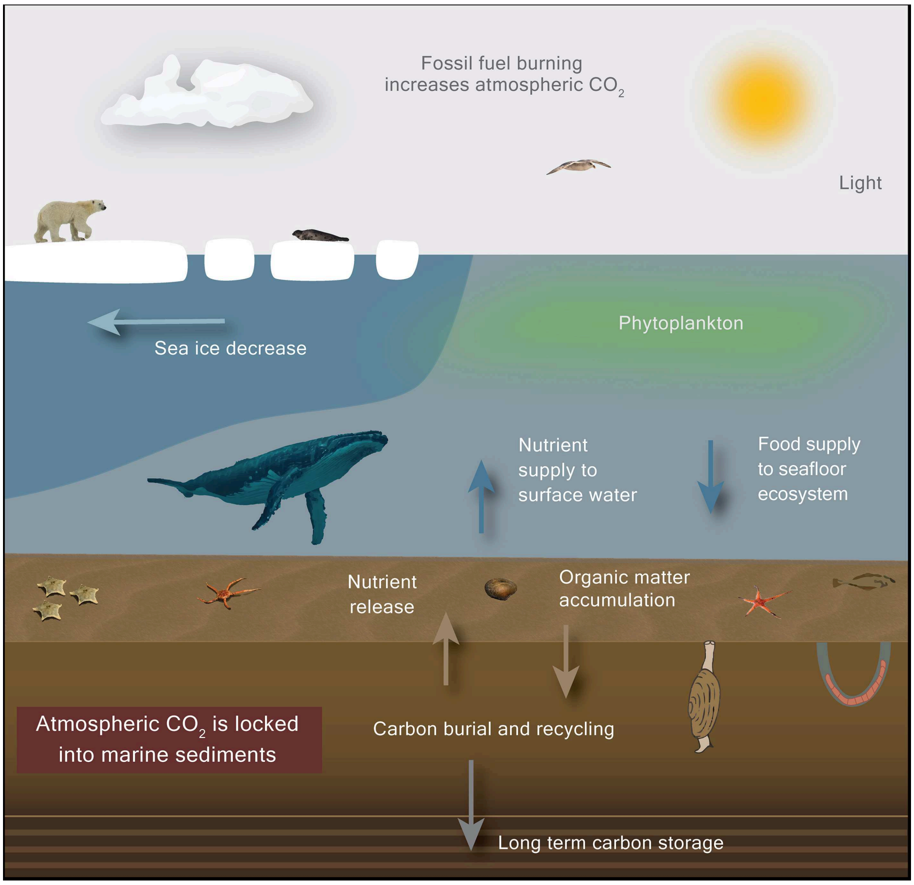

Figure 2

Figure 2

Climate change causes sea ice to melt, transforming the Arctic from an icy desert into an open ocean. Polar bears and seals may lose their habitats, phytoplankton growth may increase and fuel the Arctic food web, which may lead to higher carbon burial rates and possibly decrease the amount of CO_2 in the atmosphere.

FOOD CHAIN

Food chains begin with plant-life which converts solar energy to food by photosynthesis. Plant-eating animals get eaten by flesh-eating animals. Smaller flesh-eating animals are eaten by larger flesh-eating animals. For example, carrots are eaten by rabbits, rabbits are eaten by foxes, and foxes are eaten by bears.

CARBON

Carbon is a chemical element with the symbol C and one of the most abundant elements on the planet and in the universe. In pure form, carbon exists as graphite or diamond. It exists in all living organisms and is an important part of coal and oil. When carbon is burned, it reacts with oxygen (O) and forms a gas, carbon dioxide (CO_2).

are at the bottom of the **food chain** and therefore they are the foundation for almost any life in the ocean. But phytoplankton are more than just a food source for small and large animals like shrimp and fish. Like all plants, phytoplankton take up carbon dioxide (CO_2) from the atmosphere and, using the sun's energy, break it down into **carbon** (C) and oxygen (O_2). The oxygen is released back into the air or water. The carbon is used by phytoplankton to build their tissues. Therefore, plants have the unique ability to transform CO_2 from the atmosphere into other compounds during photosynthesis, and you will soon see why this is important.

THE CARBON CYCLE

Of the 118 known chemical elements, only a small number can be found in living organisms. Astonishingly, the immense complexity of life on Earth is made up almost entirely of only four elements: carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). For example, about 99% of your body consists of these four elements! If organisms like humans or phytoplankton die, their bodies get broken down into C, H, O, and N. During this process, the carbon is transformed back to CO_2. As we said, phytoplankton can consume CO_2 during photosynthesis,

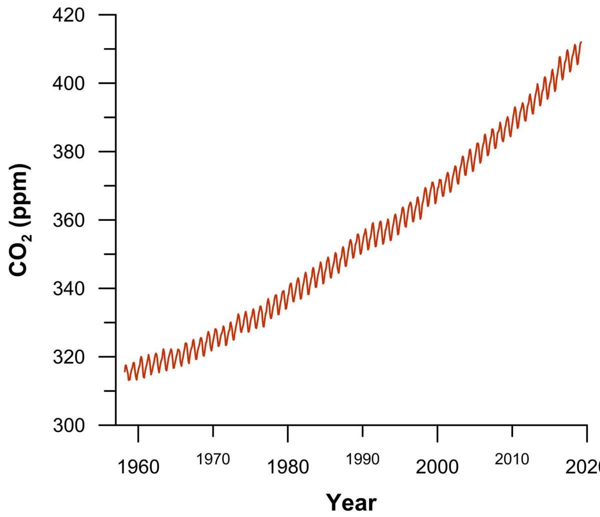

Figure 3

Figure 3

Monthly mean atmospheric CO_2 concentration in parts per million (ppm; 400 ppm = 0.04%) measured at Mauna Loa Observatory in Hawaii, from 1958 until today. The gradual increase in CO_2 is caused by burning fossil fuels. The short term up-and-down variations are mainly caused by seasonal changes in the uptake and release of CO_2 by plant growth in the northern hemisphere. Data are from: Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

which decreases the amount of CO_2 in the atmosphere. But, when the phytoplankton die and decompose, the same amount of CO_2 they took up is released back into the atmosphere. This does not just happen with phytoplankton—when the trees in the northern hemisphere lose their leaves in autumn, the global CO_2 concentration rises, and in spring, when new leaves grow back, global CO_2 concentration drops again (Figure 3). So, in nature, CO_2 is constantly being removed from the atmosphere and added back to the atmosphere. This is called the biological carbon cycle. If the production and consumption of carbon are in equilibrium, the CO_2 concentration in the atmosphere should be constant. However, large environmental changes and human activities can upset this equilibrium. For example, if a tropical forest is replaced by a desert with very few plants, the carbon stored in the forest will be released into the atmosphere and not taken back up.

Despite what you may have heard on the news, CO_2 is not always a bad guy! In fact, CO_2 is essential for regulating the temperature of our planet. Without greenhouse gases like CO_2, life on Earth would not exist because Earth's average temperature would drop to −18°C which is too cold for living things [3]. But, by burning fossil fuels, we quickly release large amounts of CO_2 into the atmosphere. Because this CO_2 cannot be taken back up as quickly as it is released by burning fossil fuels, there is an imbalance in the carbon cycle and a rise in the amount of CO_2 in the atmosphere (Figure 3). This imbalance is what drives the rapid global climate change that is causing such problems today. To better understand and predict Earth's future climate, it is very important to understand and identify the ways that CO_2 is released into the atmosphere and the ways it is removed from the atmosphere. As the Arctic changes from an icy desert into an open ocean, we need to understand how this huge environmental change in the Arctic will influence the global carbon cycle.

CARBON BURIAL IN ARCTIC MARINE SEDIMENTS

The main way to reduce the amount of CO_2 in the atmosphere for a long time is to store carbon in Earth's sediments—where it was stored until it was released by burning fossil fuels. This storage happens naturally when living things, like phytoplankton, die and sink down to the sediment on the seafloor (Figure 2). The dead organisms that reach the seafloor are a food source for other organisms living there, like starfish, worms, and bacteria. These animals consume the organic matter and break it down into its elements (Figure 2). Most of the carbon and the other elements released during this process stay in the water and feed other organisms, but a small amount of carbon gets buried and is stored in the ocean sediments. Although the amount of carbon that gets trapped this way is small [4], once it is buried it cannot go back into the atmosphere. Because oceans cover more than 70% of the Earth's surface, this process has a huge impact on the carbon cycle. We call this trapping process carbon burial, and it is a very important mechanism that has regulated CO_2 concentrations in the atmosphere, and therefore Earth's temperature, for billions of years. The processes that control carbon burial are still not very well-understood, and scientists are working to understand them better.

WILL A WARMING ARCTIC INCREASE CARBON BURIAL IN ARCTIC SHELF SEDIMENTS?

The Arctic Ocean is very deep in some areas, almost 5.5 km, but it is shallower (only 50–340 m) near surrounding land. These much shallower parts represent about half of the Arctic Ocean. Lots of phytoplankton grow in these shallow areas during summer, when there are 24 h of daylight. The growth of phytoplankton supports rich and diverse ecosystems in the ocean, on the ice, and at the seafloor, so these Arctic shelf regions are especially important for the cycling and burial of carbon. One hypothesis is that, if there are enough nutrients to support the growth of phytoplankton, the warming of the Arctic could possibly lead to large blooms of phytoplankton, which could result in more CO_2 being taken from the atmosphere and stored in the Arctic Ocean seafloor (Figure 2). But, the environmental responses to changes in sea ice are complex, variable, and not well-understood. For example, satellite observations have shown that, in some areas of the Arctic, shorter sea ice seasons and therefore longer growing seasons increased the total amount of phytoplankton, but in other areas, sea ice reductions seemed to affect water circulation, which changed nutrient availability and decreased the amount of phytoplankton.

Because CO_2 in the atmosphere is evenly distributed around the world, changes in the Arctic carbon cycle will affect the entire planet. So, changes in the amount of carbon burial in the Arctic are also important for the whole world. Much more research is needed to understand the critically important role of the Arctic Ocean carbon cycle in the global climate. Scientists around the world are involved in this huge research effort. As a recent addition to this international research effort, the Changing Arctic Ocean Seafloor (ChAOS) project is a major UK research collaboration investigating how seafloor ecosystems are affected by Arctic warming and sea ice losses, and how these changes can affect carbon burial now and in the future.

ChAOS scientists are trying to find answers to questions, such as: how will the animals and microorganisms living on the seafloor respond to changes in sea ice and ocean processes? Will a decline in sea ice increase the supply of food to seafloor ecosystems? How will seafloor organisms change the way they recycle nutrients and carbon between the seafloor and the ocean? And, how will the amount of carbon stored in seafloor sediments change as global climate change continues? The Arctic is a very remote and hostile realm, into which only very few people will ever venture. By burning fossil fuels, humans have started a huge environmental change in a region where only a few people permanently live. We can expect that major changes in the Arctic ecosystem, and effects on carbon burial, will intensify as our planet heats up further. Since changes in the polar regions affect every one of us, no matter where we live, it is crucial to answer the fundamental scientific questions, so we can better understand the effects of these immense environmental changes on human civilization.

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YOUNG REVIEWERS

CLAIRE, AGE: 15
I go to high school in New York, where I spend my time writing poetry and playing the piano.

JULIETTE, AGE: 15
My name is Juliette and I am currently in my sophomore year. In addition to my interest in science and math, I love playing chess; I learned how to play at a young age, and have been competing ever since, usually on the weekends, which is really fun. I play different sports as well, such as fencing and crew. I also love acting! I like to do black box performances at my school.

AUTHORS

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I am a marine geoscientist. My research focuses on how climate variability affects the Arctic environment. Specifically, I am investigating how changes in the Arctic Ocean sea ice cover and water mass distribution affect carbon burial in sediments from the Barents Sea. I graduated from the University Bremen, Germany and completed my Ph.D. at the Geological Survey of Norway/University of Tromsø in Norway. Since 2017, I am working in England at Leeds University. *j.faust@leeds.ac.uk

CHRISTIAN MÄRZ
A geologist by training and marine geochemist by choice, I have, over the last 10 years, studied the behavior of nutrients and metals in sediments of the Arctic Ocean and the North Pacific. My main focus is on the reconstruction of past environmental conditions from the archive of mud layers at the seafloor, and also

on the transformation and recycling processes of chemical elements like iron, manganese, carbon, sulfur, phosphorus, and silica.

SIAN F. HENLEY

I am a marine biogeochemist with a passion for the polar oceans. I am fascinated by how nutrient and carbon cycles are changing in response to climate and environmental change, why these changes are important for ocean ecosystems, and the consequences of changes occurring in the oceans for Earth's climate system. I am lucky enough to work in Antarctica and the Arctic, with inspiring people and excellent facilities. Over the last 11 years, I have traveled over 17,000 km at sea on research ships and spent over 2 years in the magnificent polar regions, surrounded by incredible wildlife and awe-inspiring scenery.

frontiers FOR YOUNG MINDS

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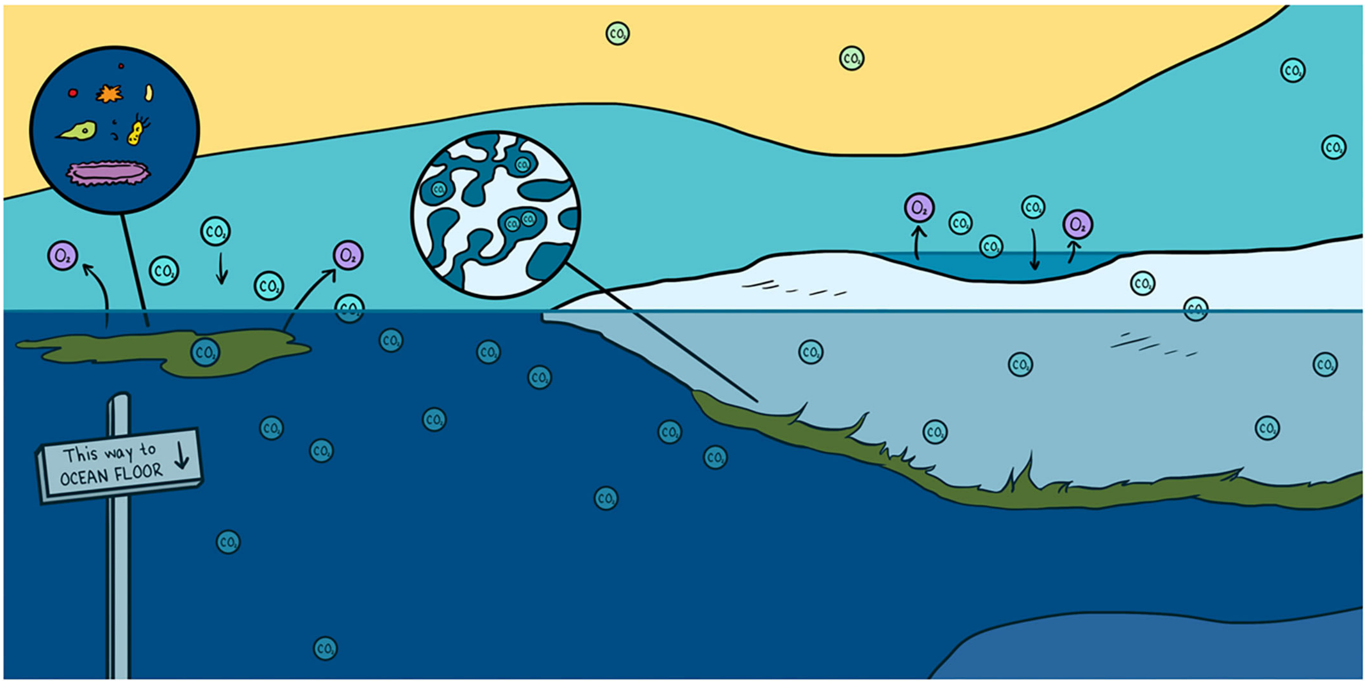

THE MOVEMENT OF CO_2 THROUGH THE FROZEN WORLD OF SEA ICE

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YOUNG REVIEWER:

JULIETA
AGE: 9

Every winter, a frozen blanket known as sea ice completely covers the Arctic Ocean. For centuries, sea ice has been viewed as a solid lid on the ocean that acts as a boundary to block gases traveling between the ocean and the atmosphere. However, scientific discoveries over recent years have shown that sea ice is more like a sponge, a porous substance that is also home to microscopic life forms. The pores in sea ice are filled with very salty liquid called brine that is rich in carbon dioxide (CO_2). These liquid pockets create a network of tubes or channels that move gases like CO_2, similar to the way veins and arteries move blood in our bodies. In this article, you will discover how CO_2 enters, exits, and is transformed in one of the harshest environments on Earth.

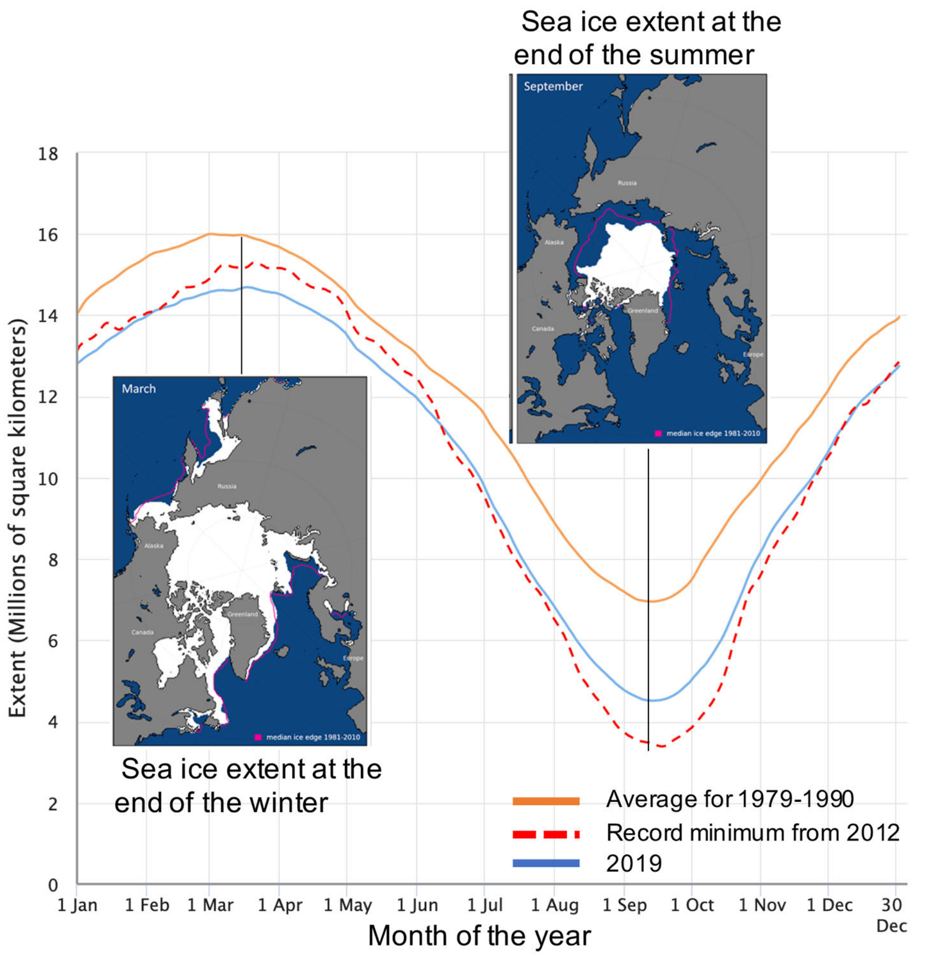

Figure 1

Figure 1

The seasonal sea-ice cycle in the Arctic. The orange line shows the monthly historical average from 1979 to 1990. The red line shows 2012, when the ice reached a record minimum. 2019 is shown in blue. The left insert shows the sea ice cover at the end of the winter 2019 and the right insert shows it at the end of the summer. Since 2000, the summer sea ice extent has drastically decreased. Maps and date are from the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder, CO.

SEA ICE: A ZOOMED-OUT VIEW

On average, **sea ice** covers about 23 million square kilometers of the Earth's oceans, or about two-and-a-half times the area of Canada [1]. Due to its size, sea ice is visible from space as a large white blanket on the ocean. By observing sea ice at these vast scales, we can see dramatic changes to the ice extent throughout the year and over decades—since 1978, when the first satellite observations of sea ice were made.

SEA ICE

Is frozen seawater that floats on the ocean surface. It is composed of ice crystal and salty liquid pocket called brine.

Each year, as the sun sets and winter begins in the Arctic Ocean (in the far North) or the Southern Ocean (in the far South of Antarctica), sea ice forms when air temperatures decrease, and the ocean begins to freeze. As winter continues, sea ice thickens and grows outwards to cover vast areas of the ocean. In some places in the Arctic, sea ice even grows to be many meters thick! As the sun rises and the air warms in the spring, the sea ice begins to melt and break up, exposing the liquid ocean below. We call this expansion and contraction of sea ice a seasonal cycle (Figure 1).

Comparing sea ice from year to year, we find that the amount of sea ice covering the ocean is changing. This long-term change is happening as the sea ice continues to grow and melt as part of its yearly seasonal cycle (Figure 1, blue and orange lines). In the Arctic, sea ice is melting more in summer than it used to, and we have already lost 30% of the summer sea ice since 1990 (Figure 2, yellow line). Scientists predict that, by 2050, all the Arctic sea ice will completely melt during summer for the first time in history. This means that, although explorers can walk to the North Pole today, in the future they will have to sail to it. One of the great research questions of our time is how these changes are affecting ocean life and our warming climate.

SEA ICE: A CLOSER LOOK

BRINE

Is water with a high concentration of dissolved salt.

Zooming in on sea ice, to the scale of only a few centimeters, shows that it is complex. Pockets of salty liquid, known as **brine**, exist in the sea ice (Figure 2). Brine pockets are liquid at temperatures below zero because the salt prevents the liquid from freezing, and there is always some liquid in sea ice [2]. Zooming in still further we find gas bubbles, salt crystals, and life within these brine pockets (Figure 2, bottom panel). These brine pockets are a unique habitat for microscopic organisms and a place where chemical reactions happen. Scientists have been working to understand sea ice at these very small scales and see how sea ice affects the chemical nature of the oceans and even life beyond the oceans.

CO_2 IN THE ATMOSPHERE, OCEANS, AND LIVING ORGANISMS

SOLUBILITY PUMP

Is a process that takes up CO_2 from the atmosphere to the ocean's surface as dissolved CO_2 and transports it to the bottom of the ocean.

BIOLOGICAL PUMP

Contributes to the ocean's role in taking up and storing CO_2 from the atmosphere. The CO_2 is transformed and stored by micro-organism as algae that use photosynthesis to grow.

Carbon is one of the most abundant elements on Earth, along with oxygen, nitrogen, and hydrogen. Carbon is found in the atmosphere as carbon dioxide (CO_2) gas, in the ocean as dissolved CO_2, in some kinds of rock, and in all living organisms. Carbon is essential to life and you are made of about 20% carbon.

In the atmosphere, CO_2 is a major gas that contributes to global warming [3]. CO_2 emitted by human activities (cars, the oil/gas industry, etc.) can move between the atmosphere, the oceans, and living organisms, and it changes forms as it moves. If CO_2 is pumped into the deep ocean, it can be locked up there for hundreds of years, reducing global warming. The processes that move CO_2 from the atmosphere into the ocean are called pumps. There are two main CO_2 pumps in the ocean: the **solubility pump** and the **biological pump**. Oceans have already absorbed one-third of the CO_2 emitted by human activities thanks to the solubility and biological pump.

The solubility pump (Figure 3, blue arrows) refers to the process by which atmospheric CO_2 is absorbed by the ocean surface and become

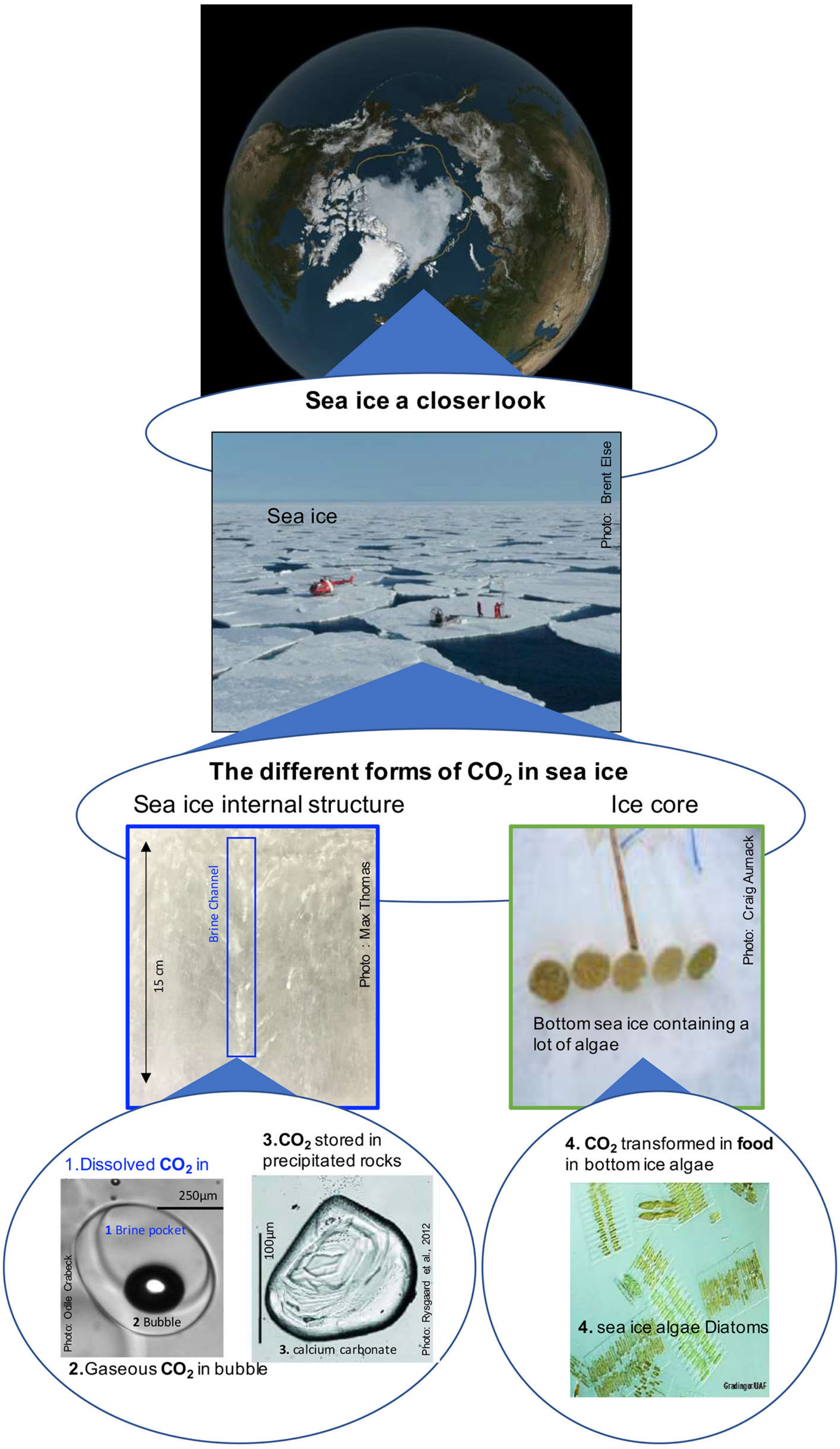

Figure 2

Figure 2

Sea ice a closer look. On the top panel, a satellite view of the Arctic Ocean at the end of summer 2019. The yellow line shows the historical (1979 to 1990) extent of the sea ice summer cover. We can observe that there is now less ice in the Arctic during the summer. Before the summer sea ice cover was reaching beyond the yellow line. The middle panel shows scientists sampling sea ice during the summer season. The bottom panel shows on the left-side the sea ice internal structure and on the right-side, ice cores that contain a lot of algae at the bottom. This bottom panel shows also, where the CO_2 is trapped in sea ice:

1. In brine where the CO_2 is stored in a dissolved state,
2. In bubbles where the CO_2 is stored in gas phase,
3. In crystals of calcium carbonate where the CO_2 is stored in solid form as rocks,
4. In sea ice algae where the CO_2 is stored as carbon (sugars food) (http://www.arcodiv.org/seaice/diatoms/IceDiatoms.html).

dissolved in the surface ocean. Once the CO_2 is dissolved, it can be transported deep into the ocean by the ocean currents. The capacity of the ocean to take up CO_2 from the atmosphere depends on the water temperature and salinity (saltiness). Cold, freshwater can absorb

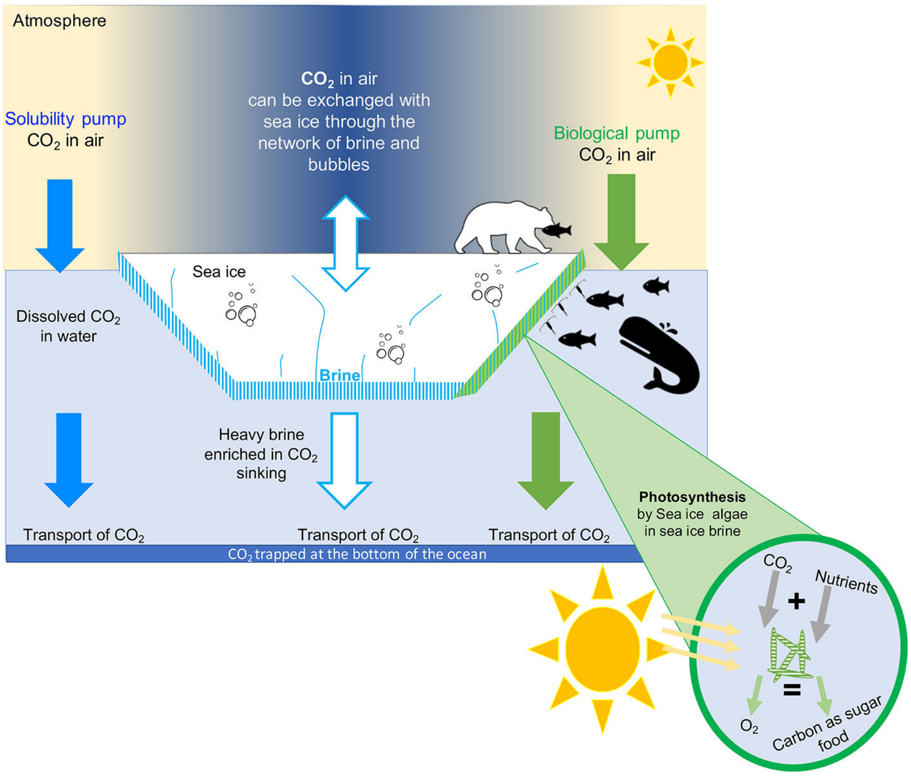

Figure 3

Figure 3

How does CO_2 move from the atmosphere into the ocean? CO_2 is found in the atmosphere as a gas. This CO_2 can dissolve in the seawater. Once in the seawater, it can be transported by currents to the bottom of the ocean. We call this the solubility pump (blue arrow). Sea ice can also exchange CO_2 with the atmosphere. The CO_2 in sea ice is either dissolved in brine or stored as gas in bubble or in solid phase as calcium carbonate rocks. Some of the brine containing CO_2 is rejected to the underlying seawater and transported to the interior part of the of the ocean. This process trapped CO_2 at the bottom of the ocean for a very long time (white arrow). Sea-ice algae also use CO_2 to grow, through the process of photosynthesis. We call this the biological pump (green arrow). The CO_2 stores in algae as food can move up the food chain as the algae is eaten by grazers, which are then eaten successively by larger animals.

PHYTOPLANKTON

Are single-celled algae that live at the surface of the ocean and use the photosynthesis process to grow. The most common types of phytoplankton are Diatoms. Phytoplankton form the base of aquatic food webs. They are used as food supply by small fish and other marines' animals.

more CO_2 than warm, salty water. Therefore, the cold polar oceans, like the Arctic Ocean, are great at taking up CO_2 from the atmosphere. If the CO_2 goes to the bottom of the ocean, it can stay there for 1000 years or more (Figure 3).

The biological pump refers to the use of CO_2 by algae called **phytoplankton**. Algae are microscopic, single-celled organisms that grow using sunlight, nutrients, and CO_2 in the chemical process of **photosynthesis** [4] (Figure 3, green arrows). Many phytoplankton live floating in the world's oceans. Because algae use CO_2 to grow, they help the ocean to take up CO_2 from the atmosphere (Figure 3, green arrows). Some of these algae are specialized to live in the unique environment provided by sea ice, including in the liquid brines.

HOW DOES SEA ICE ALGAE TRANSFORM CO_2?

I am only as big as a cell. I breathe in CO_2 and breath-out O_2. I live in salty brine pocket, and I get my energy from the sunlight. Who am I? I am a sea ice algae.

Ice algae grow in brine pockets within the ice, in meltwater ponds at the surface, and most importantly at the base of sea ice, where the ice is touching the ocean below. Ice algae grow quickly, or

bloom, when light becomes available for photosynthesis in the spring (Figure 3, green arrows). Ice algae known as diatoms are very good at growing quickly and largely make-up the ice-algae bloom. Although the diatoms are too small to count individually, scientists can see the bloom as a browning of the ice (Figure 2, bottom panel). The ice-algae bloom lasts until late summer when the cells have used up the nutrients needed to grow and when the ice around them begins to melt. Photosynthesis performed by ice algae can have a large impact on how much CO_2 sea ice takes up in the spring (Figure 3, green arrows). Generally, when the ice is brown with algae, it is expected that lots of CO_2 is being taken up into the ice (Figure 2, bottom panel). Ice algae play an important role in using atmospheric CO_2, but they are also important for the animals living in the Arctic Ocean. The growth of ice algae supplies other organisms with a lot of food. The size of the algae bloom means that organisms can get lots of food very easily, like going to a vegetarian buffet for dinner. Nutrition gained from ice algae is transferred up the food web as one organism eats another, all the way to the polar bear.

PHOTOSYNTHESIS

Is the process by which plants and algae make food. This chemical process uses sunlight, CO_2, and nutrients to produce sugars that the cell can use as energy to grow.

BLOOM

Is a rapid increase in the population of algae. An algal bloom is often recognized by the green or brown coloration of the water.

WHAT HAPPENS TO CO_2 TRAPPED IN SEA ICE?

As sea ice forms in winter, it traps salts and CO_2 from the ocean in brine (Figure 2, bottom panel). In fact, so much CO_2 gets trapped with salt that it is transformed into solid rock by chemical reactions. One of the most common rocks that forms from CO_2 inside sea ice is made of **calcium carbonate**, also called limestone, which is the same substance that makes up the skeletons of corals and many seashells you might find on the beach. Researchers can see the tiny pieces of calcium carbonate when they melt a core of sea ice and look at it under the microscope (Figure 2, bottom panel). The CO_2 in sea ice is also trapped in bubbles (Figure 2, bottom panel). The bubbles can rise from the bottom of the sea ice to the surface through the brine channels. Once at the surface, the gases can escape into the air (Figure 3, white arrows). Sea ice also sends some CO_2 to the bottom of the ocean. This process takes place during winter, when the salty brine from the sea ice sinks to the deep ocean, bringing CO_2 along (Figure 3, white arrows). This is often referred to as the sea-ice pump, similar to the solubility and biological pumps described above. Through the rising bubbles and sinking brine, the sea ice loses a lot of CO_2 that was trapped inside it. As a result, when the sun comes back in the spring, the sea ice no longer holds as much CO_2. Researchers have observed that, in the spring, sea ice can again absorb lots of CO_2 from the atmosphere. Overall, researchers think that sea ice helps the ocean to absorb CO_2. So, sea ice helps us fight climate change.

CALCIUM CARBONATE

Is a sedimentary rock like limestone. Calcium carbonate is produced by the precipitation (solidification) of dissolved calcium and CO_2 in water.

KEY MESSAGES

Sea ice cover grows in winter and melts in summer. Thanks to the cold water and the presence of algae and sea ice, the Arctic Ocean is a carbon sink; it helps to decrease the amount of CO_2 in the atmosphere. Firstly, sea ice algae use CO_2 to grow and create food for larger organisms. Secondly, sea ice can trap CO_2 in its brine and favor its transport to the bottom of the ocean. In the Arctic, the summer sea ice cover is strongly decreasing due to global warming. Global warming threatens the house of ice algae and the ability of the Arctic Ocean to exchange CO_2 with the atmosphere.

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YOUNG REVIEWER

JULIETA, AGE: 9

Hi, my name is Julieta I was born in Minnesota (United States of America) but now I moved with my family to Uruguay. I speak English and Spanish. I like roller skating and making pottery. At school my favorite subject is Math.

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Karley Campbell is an Associate Professor of Marine Botany at The Arctic University of Norway, and an affiliated researcher at the University of Bristol, UK. Her research brings together lab and field-based studies to determine how environmental change will affect on sea ice microorganism activity, species composition and physiology.

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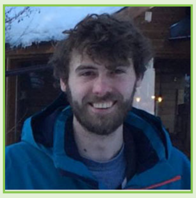
Sebastien Moreau is a sea ice and ocean biogeochemist working at the Norwegian Polar Institute, Tromsø, Norway. His research focuses on phytoplankton and the biogeochemical cycle of carbon of polar oceans. He investigates these questions by using field observations, satellite data as well as 1D and 3D models.



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frontiers FOR YOUNG MINDS

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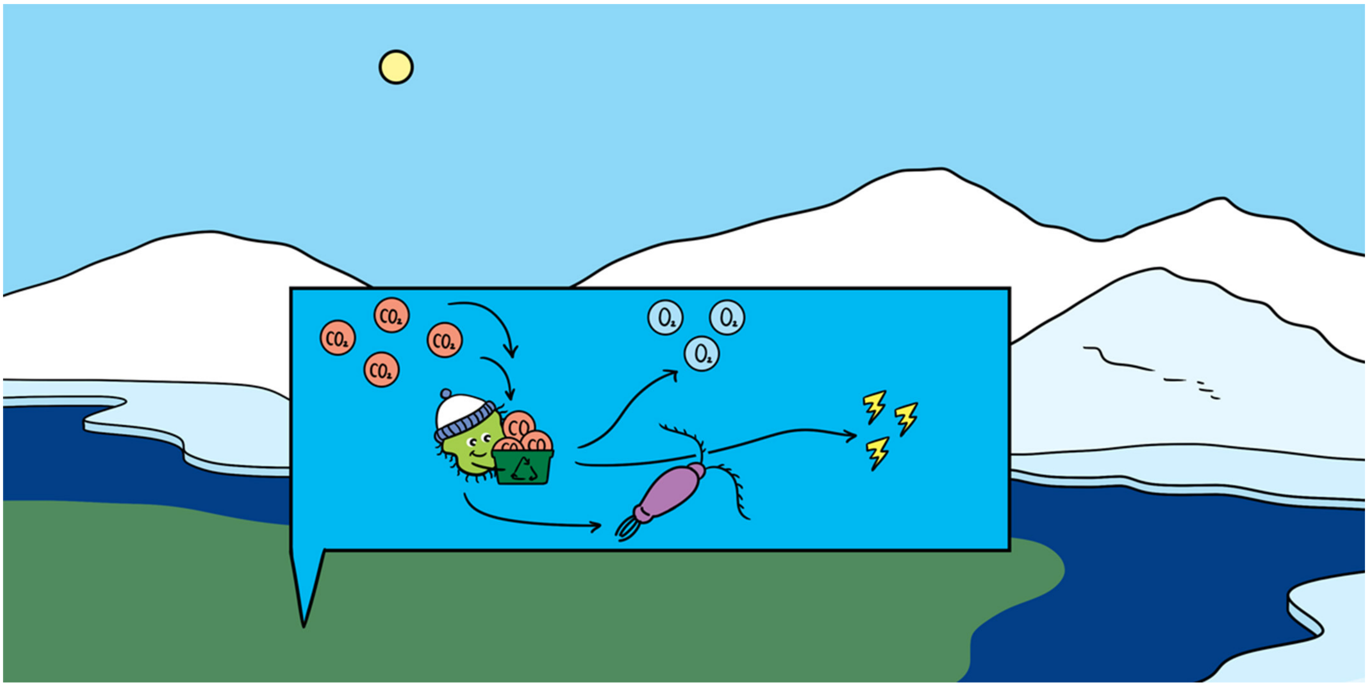

REDUCE, REUSE, RECYCLE IN THE ARCTIC OCEAN WITH THE POWER OF MICROBES

Birthe Zäncker[1†], Rowena F. Stern[1†], Elliott L. Price[1,2] and Michael Cunliffe[1,3]*

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YOUNG REVIEWERS:

MODBURY PRIMARY SCHOOL

AGES: 10-11

Did you know that microbes, too small for the human eye to see, far outnumber and outweigh all animals? Microbes that live in the Arctic carry out a surprising variety of roles recycling food. Despite the cold temperatures, Arctic waters are nutrient rich, which allows a type of microbe called single-celled algae to grow in huge numbers. Only cold-adapted microbes can survive though in waters that sometimes reach temperatures even below freezing! Microscopic algae use carbon dioxide (CO_2) and the sun's energy to grow, helping to reduce levels of CO_2 in the atmosphere. Microscopic animals called zooplankton eat smaller microbes. All microbes excrete waste and eventually die. The resulting products are not wasted, though. Other microbes called bacteria and fungi are expert recyclers and break down the dead organisms to more basic forms of chemical energy that are reused by single-celled algae and other microbes.

WHY ARE MICROBES SO IMPORTANT?

Microbes are microscopic organisms that are formed from a single cell. Did you know that 1 L of seawater contains billions of microbes [3]? Due to the sheer size of our oceans, this means that there are 100 billion times more microbes in the oceans than there are stars in the known universe! There are thousands of types of microbes that researchers are still discovering. Some are carnivores, some are herbivores, and some are omnivores, like fungi, bacteria, **zooplankton**, and phytoplankton. Microbes are the base of the food web and support all larger organisms, because of their sheer numbers. In fact, marine microbes make up 70% of the total living mass of all oceans [1]!

MICROBES

A variety of single-celled organisms including algae, bacteria, viruses, and fungi. Algae can use photosynthesis to make complex nutrients like sugar from sunlight and carbon dioxide (CO_2). Carnivorous microbes help recycle nutrients.

ZOOPLANKTON

Microscopic animals that eat microbes. Zooplankton are primary consumers.

Microbes not only support all life as we know it, but they also play an important role in providing half of the oxygen we breathe and regulating the earth's climate. Some microbes can take up CO_2, a gas that can trap heat in our atmosphere and contribute to global warming. Thanks to microbes, the deep ocean and sediments contain almost half as much CO_2 as we can find in the atmosphere. CO_2 trapped in the deep ocean cannot contribute to global warming, so CO_2 uptake by the oceans is good for our planet. The CO_2 uptake is not the same across all oceans though. The Arctic Ocean tends to take up an especially large amount of this gas. Despite the importance of the Arctic Ocean for regulating the CO_2 in our environment, we know very little about this ocean.

WHY DO WE KNOW SO LITTLE ABOUT LIFE IN THE ARCTIC?

Learning about the Arctic and the organisms that live there is extremely difficult because this ocean is largely inaccessible. For much of the year, thick ice prevents any ships from entering and the weather is too rough to carry out experiments. Because of this, we only see snapshots of the processes that happen in the Arctic, mostly in the summer months. Conditions in the Arctic Ocean are hostile, with long, freezing winters and short, cool summers. Average air temperatures in winter can fall to −34°C and rise up to 10°C in the summer, although the ocean temperature remains steady at around −1.5 to −3°C. Much of the water is locked up as ice. Depending on how far north you are, there can be up to almost half a year of complete darkness during the winter, or 24-h of daylight during the summer.

ALGAE

Algae are plants living in the water. They can range from single-celled organisms (see microbes) to huge plants up to several meters high. Just like plants on land they need sunlight to survive.

A lot of microbes live in or attached underneath sea ice. The ice that forms on the Arctic Ocean is not as solid as you might think. Numerous tiny water channels permeate the ice (Figure 1). These channels carry very salty water and are called brines. Lots of microbes, including **algae**, fungi, and bacteria, live and eat in the brines.

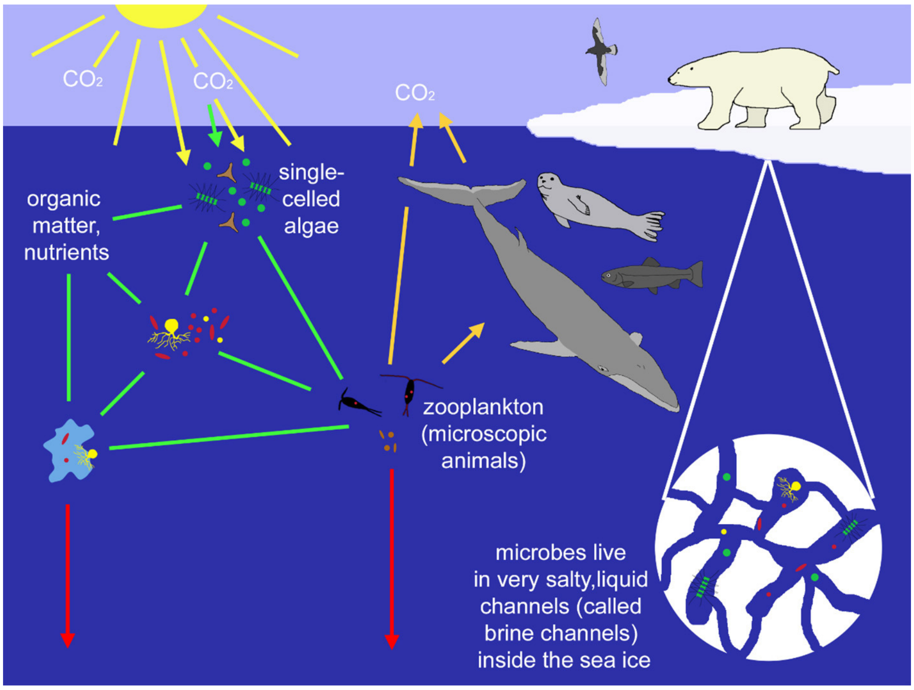

Figure 1

Figure 1

A typical Arctic food web. The arrows and lines show connections between animals, microbes, and the food/nutrients they consume. The microbial loop (___) begins with primary producers producing organic matter. Carbon drawdown (→) shows food waste or excreted matter sinking to the bottom of the ocean. Transparent exopolymer particles (TEP) help with carbon drawdown and are a food source for microbes, recycling energy into the microbial loop. Primary consumers like zooplankton feed on microbes and in turn are eaten by larger animals, transferring the energy to the top predators (→). Note: organisms not to scale.

PRIMARY PRODUCER

Primary producers can directly use energy obtained from the sun or chemicals and use this energy to create cell building blocks like sugars and other nutrients.

PHOTOSYNTHESIS

Plants can use the energy from the sunlight. With the help of the sunlight, they take water, carbon dioxide and minerals and produce oxygen and sugars needed for cell growth. This process is called photosynthesis.

When scientists do get the rare chance to go to the Arctic on big research icebreakers, they need to prepare themselves thoroughly for the hostile conditions (Figure 2). Thick clothes are needed, and the scientists and crew must protect themselves from the harsh sunlight by wearing proper sunglasses and sunscreen. Even with all the precautions, the scientists still need to take breaks from working on the ice or on deck.

So, what do these harsh conditions mean for microbes that have to live in the Arctic all year round? Microbes have acquired several survival strategies to withstand the cold, such as making anti-freeze molecules to prevent ice from forming inside them, which would otherwise make them burst. Algae cells contain fats that help them to float on the surface, to capture the weak light during winter season. Other microbes go into hibernation, quite similar to some bears. In the spring and summer, microbes grow and reproduce to large numbers very quickly.

HOW DO ARCTIC MICROBES REDUCE, REUSE, RECYCLE AND DECIDE HOW MUCH CO_2 FROM THE ATMOSPHERE REACHES THE SEDIMENT SEVERAL KILOMETERS BELOW THE OCEAN SURFACE?

Single-celled algae are called **primary producers**, because they can live directly from sunlight without the help of other animals or plants. Through the process of **photosynthesis**, these algae can make sugars

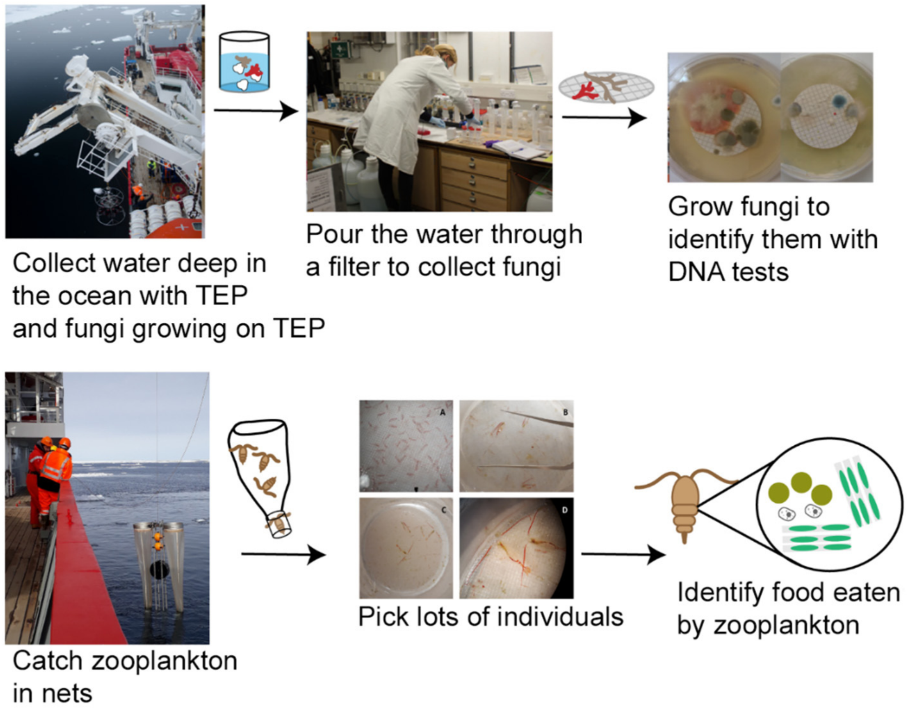

Figure 2

Figure 2

How we investigate Arctic microbes on the ship James Clark Ross. (Top) Birthe Zäncker (top middle) is finding out what types of fungi live on transparent exopolymer particles (TEP) and how they contribute to moving carbon into the deep ocean. (Bottom) Elliott Price uses special laboratory tests to identify what zooplankton have eaten and the amount of nutrients they have obtained (pictures courtesy of E. Price, J. Hopkins, R. Jeffries, L. Norman, B. Zäncker, D. Conway).

PRIMARY CONSUMER

A primary consumer eats primary producers.

and other compounds from CO_2, using water and sunlight. All other organisms depend on these algae as a source of food. Zooplankton are **primary consumers**, which means that they directly eat the algae, the primary producers (instead of eating other animals), and they can grow in huge swarms. Whales, seals, and fish eat zooplankton, and finally, top predators, such as polar bears feed on the fish and seals. Figure 1 shows a summary of a typical Arctic food web.

Not all the food is eaten though, and the leftover food turns into waste. In addition, just like us, microbes have to poop. All that waste cannot simply be flushed down the toilet. Microbes help with disposal of waste, especially in the summer when growth is at its highest. Specialized microbes, such as some bacteria and fungi, can break down leftover food into small particles that contain essential nutrients. These particles can be eaten by other microbes, such as algae, so that the whole process can start again, thus re-using the nutrients once again and reducing the waste that sinks to the bottom of the ocean. What about the CO_2 that is produced by millions of microbes as a waste product? This is recycled by algae as they grow and perform photosynthesis. The overall gain or loss of CO_2 in the ecosystem depends on the balance between its creation as a waste product and its use in the process of photosynthesis.

Did you know that fungi not only grow in forests, where we can see them growing as mushrooms on old tree branches, but they also grow abundantly in the ocean? Just like in the forest, marine fungi help to break down dead organisms and the waste products from living cells.

In the ocean, fungi shapes range from simple, round cells to cells with tiny tentacles called hyphae (Figure 1), which help the fungi to attach to other organisms and particles.

The recycling of waste does not work perfectly, though. The melting sea ice makes the water cold and less salty. This produces very dense water that sinks to the bottom of the ocean, taking with it particles and organisms suspended in the cold water before the microbes at the surface have time to recycle it. When they reach the bottom of the water column, these particles and organisms become trapped in the sediment, locked away for millions of years. This is called **carbon drawdown** (Figure 1). Carbon drawdown is beneficial because the carbon is kept out of the atmosphere and does not trap the heat around our Earth.

CARBON DRAWDOWN

The process of carbon being drawn down to the bottom of the ocean when food or animals sink (called marine snow), removing the carbon from the ocean's surface.

In addition to marine microbes, researchers have found that jelly-like particles, called transparent exopolymer particles (TEP) also play an important role in carbon drawdown. The TEP are very sticky and can trap cells and other particles on their surfaces. These clumps can get heavy and sink quite rapidly down into the deep ocean, bringing carbon-containing molecules into the deep ocean, also benefiting the atmosphere.

HOW DO WE TRACK THE RECYCLING OF MICROBIAL WASTE IN THE ARCTIC OCEAN?

We need to understand how the recycling of carbon in the surface layer of the ocean works to predict how climate change will affect this process in the future. Climate change describes the warming of the Earth. Over the last century, the Earth has warmed by 0.87°C on average [2] due to an increase in CO_2 from human activity. This might not seem like much, but it has a significant effect on life, especially in the Arctic where the warmer temperature makes sea ice and glaciers melt more quickly. When most of the glaciers are gone, the Arctic will lose its source of cold, fresh water from the ice, so eventually the Arctic Ocean will become warmer and saltier. We know that the melting ice will have a negative effect on the seals and polar bears that depend on sea ice to hunt and raise pups. At the same time, less ice means that more light can get through to the water, allowing new kinds of algae to grow, photosynthesize, and draw down CO_2. The growth of new kinds of algae in warmer water might offset the loss of sea ice algae.

The information we collect about microbes through our experiments will allow us to identify what the microbes eat and the amount of nutrients transferred from algae up to seals. The amount of nutrients larger animals are able to obtain will determine how well they are able to adapt to a changing Arctic Ocean.

SUMMARY

In summary, microbes are crucial to the Arctic ecosystem. They carry out key functions including providing food for other organisms and recycling nutrients for reuse by other microbes. The microbes feed larger Arctic animals, which enables the animals to survive the harsh conditions. Microbes reduce the carbon concentration in the atmosphere through carbon drawdown. This helps reduce the warming of our planet. We still do not know enough about what exactly these microbes are, what they do, or how climate change will affect them. Our work is to understand how well Arctic microbes can adapt to climate changes and whether future microbes, as the base of the food web, will provide more or less food for predators, such as fish, whales, and polar bears.

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YOUNG REVIEWERS

MODBURY PRIMARY SCHOOL, AGES: 10–11

We really enjoyed learning about real-world scientific research and how it is important to help us care for our planet. We are Will, Tom, Jasmine, Jay, Maddie, Angus, Lizzie, Jamie, Matilda, Zoe, Emily, Isaac, Fin, Ella, Martha, and Rose.

AUTHORS

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I work as a post-doc at the Marine Biological Association in Plymouth, UK, focusing on bacteria and fungi in polar regions. I look at what bacteria and fungi in the sea and the ice eat and how that influences the carbon cycle. In particular I am interested in jelly-like particles (TEP) and their involvement in organic matter transport. To do that, I get to do what I love and go on research cruises to the Arctic and Antarctic. When I am not on a ship, I enjoy being out in nature as well as reading and writing about science and the oceans.

ROWENA F. STERN

I am a microbial ecologist at the Marine Biological Association. I received a Genetics degree at the University of Aberdeen and a PhD in parasitology from the University of Glasgow. I have worked in medical and ecological research in the UK and Canada. I use genetic methods to identify microbes from historical oceanic samples from as far back as 60 years ago. Using this unique long-term perspective, I am looking at how marine microbes respond to environmental changes over many years, such as those caused by climate change. *rowena.stern@mba.ac.uk

ELLIOTT L. PRICE

I am a marine ecologist with an interest in exploring the impacts of stressors on the structure and dynamics of food webs. As part of the ARISE team within the Changing Arctic Ocean project, I am working toward my Ph.D. looking at how contemporary climate change is affecting mesozooplankton (mid-sized zooplankton) assemblages, primarily copepods, in the Arctic Ocean, and the consequences this may have across the food web.

MICHAEL CUNLIFFE

I received a degree in environmental biology from the University of Liverpool, and a M.Sc. and Ph.D. in Microbiology from the University of Manchester. After a post-doc at the University of Warwick, I joined the Marine Biological Association (MBA) in 2010 as a Research Fellow. Since 2014, I am a MBA Senior Research Fellow and Associate Professor of Marine Microbiology. I lead a research group at the MBA that studies a range of topics in microbial biology and ecology, from microbe-invertebrate interactions in coastal sediments to microbial biogeochemistry in the open ocean and polar seas.

[†]These authors have contributed equally to this work

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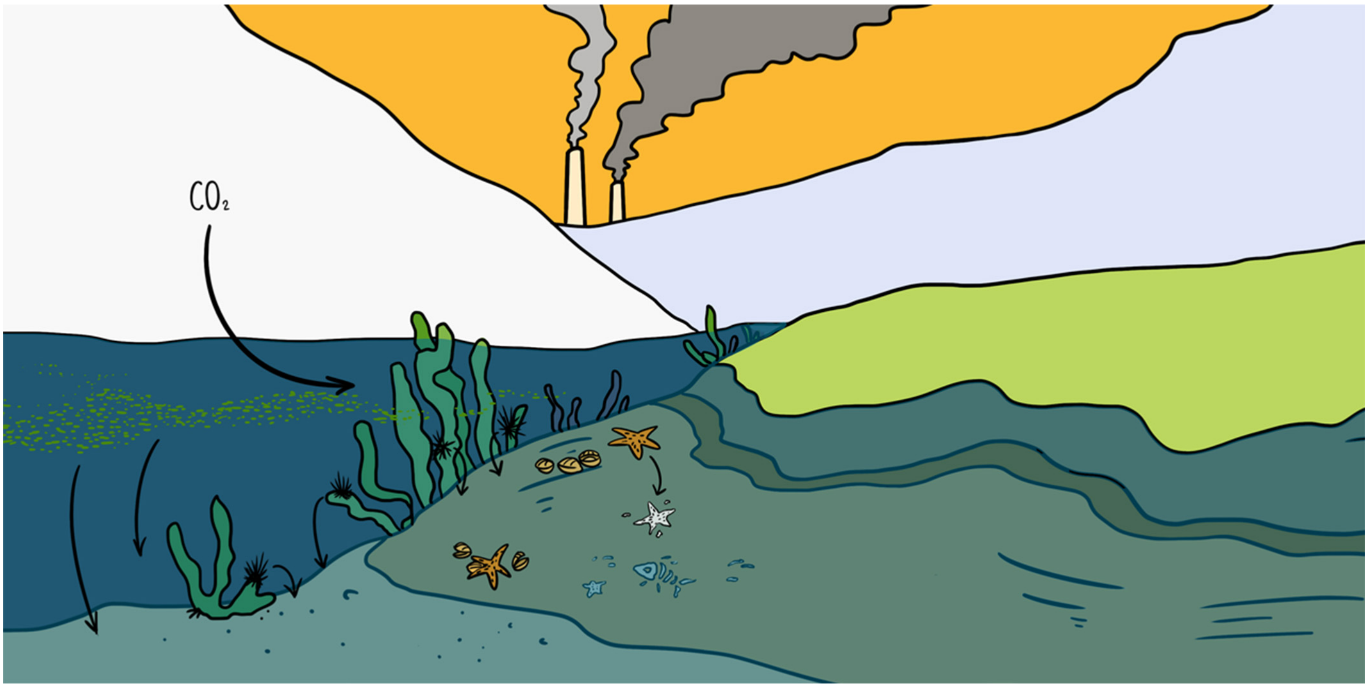

WHAT IS BLUE CARBON AND WHY IS IT IMPORTANT?

David K. A. Barnes*

British Antarctic Survey, NERC, Cambridge, United Kingdom

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BUFFALO MUSEUM OF SCIENCE
AGES: 14–18

The Earth's warming climate is reducing snow and ice. The warming of the polar seas causes the sea surface to freeze less in winter and glaciers to retreat, generating more open, ice-free water. Less sea ice provides a longer growing season for marine plants called microalgae (phytoplankton) and removes more carbon, in the form of carbon dioxide, from the atmosphere. The growth of microalgae provides more food for animals that eat the algae and store this carbon through growth of their bodies. The carbon stored by marine life is called blue carbon. When marine animals die some of the blue carbon is buried in the seabed, and that carbon is removed from the carbon cycle. This trapping of carbon in the seabed or in other places is called sequestration. The amount of polar blue carbon increases with climate warming. This is known as negative feedback on climate change. Any negative feedback on climate change is important to help combat global warming. In this article explains what we have learned from measuring blue carbon.

THE CARBON CYCLE AND BLUE CARBON

The element carbon is critical for all life forms. Carbon cycles between the atmosphere and earth's surface. There is carbon dissolved in the sea, stored by organisms in their bodies, buried in soil, and stored in rocks, and in the carbon cycle, carbon moves between these sources. In the atmosphere, carbon is present as the gas carbon dioxide (CO_2). On land, CO_2 can be used by plants in a process called photosynthesis. In photosynthesis, plants use sunlight to turn CO_2 into food, which they use to build new plant tissue. Some of the carbon in plants is returned to the atmosphere as CO_2 through plant respiration. Plants can be eaten by animals, which breathe CO_2 back into the atmosphere and use some of the remaining plant carbon to build their own bodies. When plants and animals die, the carbon in their bodies is returned to the atmosphere as CO_2 as bacteria break down the dead organisms. Long-lived trees or the plants and animals that are buried in wetlands can sequester carbon, which means removing it from the carbon cycle, for over a century. Over long time periods, pressure can convert this buried carbon into oil, coal, or rocks, such as limestone. Volcanic activity or the burning of fossil fuels by humans can return this sequestered carbon to the atmosphere as CO_2. CO_2 from the atmosphere can then dissolve into the sea, and there the cycle can start again.

BLUE CARBON

Carbon stored by marine life.

PHYTOPLANKTON

Tiny plants or micro-algae that capture carbon.

CARBON CAPTURE

Fixing carbon dioxide gas into storage away from Earth's atmosphere.

CARBON SEQUESTRATION

Removal of carbon from carbon cycling (e.g., by burial).

Blue carbon is the part of the carbon cycle that involves sea-life. This part of the cycle happens in three stages. Marine plants, such as seaweed and microalgae called **phytoplankton** take up atmospheric CO_2 when they perform photosynthesis. This is known as blue **carbon capture**. Polar animals eat these phytoplankton and seaweeds and use the carbon in these plants to build their tissues and skeletons. This is known as blue carbon storage. Organisms with a high proportion of skeleton, such as corals, have more chance of protecting that carbon from bacterial breakdown when they die. These organisms are said to immobilize carbon. When blue carbon is removed from the carbon cycle for more than 100 years, for example when marine life dies and is buried on the seabed, this final stage is called blue **carbon sequestration**.

CARBON SINKS AND FEEDBACKS IN A CHANGING CLIMATE

Greenhouse gases, such as CO_2 and methane (CH_4) help trap heat in the Earth's atmosphere. Our use of fossil fuels has increased atmospheric CO_2, which traps heat near the earth and warms our planet. As a result, the polar regions are losing snow and ice [1]. Land is darker than the white of ice, so ice-free areas absorb heat faster and this in turn melts even more snow and ice. This is called a positive feedback mechanism, which intensifies climate warming. However, ice loss also frees up new space for plant or animal life. Since plants and animals take up carbon to build their bodies, they are examples of carbon sinks. A carbon sink is an area in where there is a net accumulation of carbon which has come from the atmosphere (such as prolific growth of micro-algae; an algal bloom). Plants use atmospheric CO_2 to grow, so new ice-free spaces lead to a *reduction* in atmospheric carbon, reducing climate warming—this is called a **negative feedback** mechanism [2]. In this way, the sea can provide a lot of negative feedback for climate warming [3].

NEGATIVE FEEDBACK

The mitigation or (reduction) of an effect by its own influence.

Sequestration of carbon usually happens through the burial of plants or animals in wet sediments. This is why most fossils are found in rocks that were once sediments of seabeds, lake bottoms, or swamps. In the sea, negative feedback can happen when less of the polar sea surface freezes in winter, resulting in more light penetrating the water so phytoplankton can grow for a longer time. When the phytoplankton die, some of them become buried on the seabed, sequestering the carbon. Others are eaten by animals, and some of these animals are eventually buried in the seabed, too. So, greenhouse gas warming can result in less winter sea ice, which leads to more carbon being sequestered on polar seabeds, thereby reducing atmospheric CO_2. Retreating glaciers free up even more space for light and marine life, driving a similar negative feedback. Climate warming can also cause major changes in ice shelves. Ice shelves are where polar ice caps meet the sea and flow into it in the form of huge, floating, frozen rivers. Extensive ice shelves along the Antarctic Peninsula have been breaking up at their seaward edge to form giant icebergs. This not only opens new areas for life to capture and store carbon, but as the icebergs drift away on currents, they release nutrients. These nutrients, such as iron frozen in from dust on the land, fertilize phytoplankton elsewhere in the ocean [4]. Icebergs can also collide with the seabed in what is termed **ice scour**, crushing benthos putting carbon back into the carbon cycle. Major projects, such as the Changing Arctic Ocean programme (https://www.changing-arctic-ocean.ac.uk/), bring teams of scientists together to try to measure and understand the physical and biological changes that are caused by a warming climate.

ICE SCOUR

Collisions between icebergs and the seabed.

HOW DO WE MEASURE BLUE CARBON?

In order to determine whether the loss of sea ice affects the amount of blue carbon, we first had to carefully select the sampling sites. The sampling sites chosen for the Changing Arctic Oceans Seabed (ChAOS) study span the length of the Barents Sea (Figure 1), because it is important to take measurements in locations that have different amounts of past and present sea ice. In other ways, the chosen sites are quite similar, for example in terms of water depth and seabed characteristics. These similarities make it easier to interpret any differences between the blue carbon found at these sites. Sampling is performed each summer, the time when it is

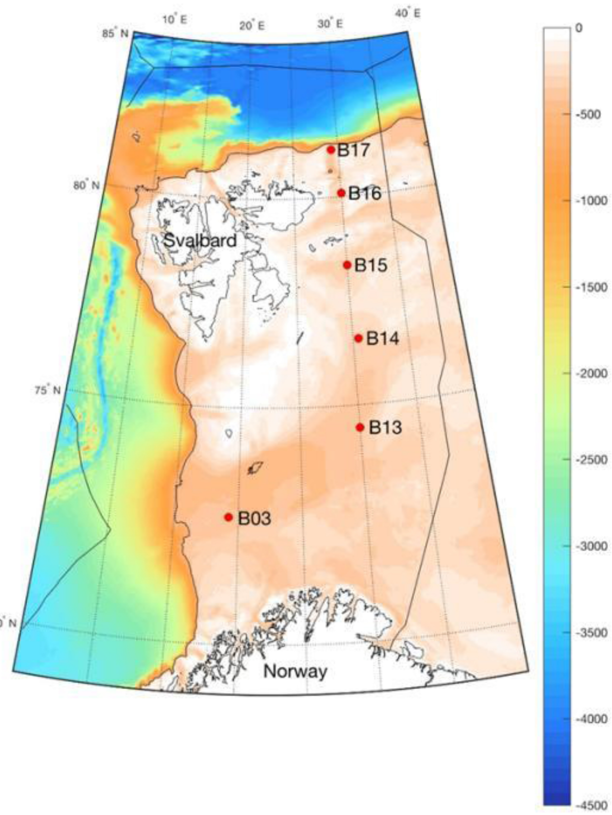

Figure 1

Figure 1

Sampling sites of the Changing Arctic Ocean Seabed project in the Arctic Barents Sea. Each red dot represents a site where samples are collected. The color scale shows the depth of the seabed in meters.

easiest for ships to travel through the Barents Sea. Sampling all sites at the same time of year also helps to reduce complicating differences between sites.

Phytoplankton can be collected in water samples or plankton nets, and care is required to make sure precise water volumes are investigated, so that density and mass per volume can be calculated. The density, size, and identity of life on the seabed (otherwise known as **benthos**), can be determined using photographs from a high-resolution camera that is lowered to the seabed on a tripod. The organisms can also be collected in samples of sediment. Chemical tests are then used to investigate how much carbon is present at each depth. Animals are dried and weighed in a way that allows scientists to calculate how much of the weight is made up of soft tissue and how much is made up of skeleton. At each site, many samples are taken to allow for variability in environmental factors, such as sea temperature, water flow, salinity, dissolved oxygen, material of the seabed (such as rocks, sand, or mud), and seabed roughness.

BENTHOS

Organisms (mainly animals) that live on the seabed.

WHAT CAN SAMPLING TELL US ABOUT BLUE CARBON?

The sampling procedure described above can provide a lot of information about the amount of carbon present in organisms of

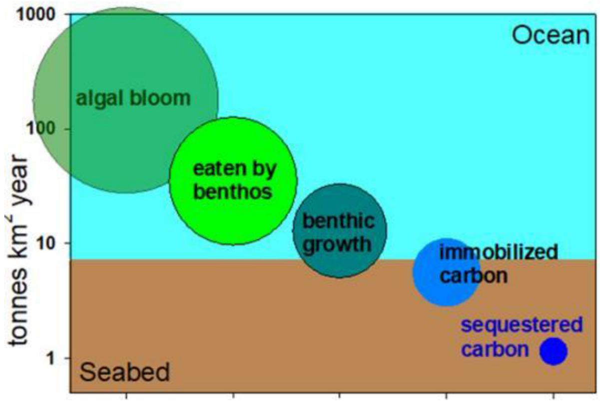

Figure 2

Figure 2

A carbon cascade in a polar sea. Only a small proportion of an algal (phytoplankton) bloom (left) is eaten by benthos, which are animals living on the seabed. In turn only a small proportion of that turns into animal tissue (benthic growth). Less than half of that carbon is "immobilized" in the skeletons of animals and only half of 1% may be sequestered through burial. Sequestration is defined here as removal from the carbon cycle for more than 100 years.

different types and sizes from different sites. The method can also provide information on the number or density of each organism type. Calculations can then be made of how much carbon is held by organisms in each sample at each site. If sample 1 contains three clams, 10 worms, and a sea star, the carbon for each organism type can be totaled and all organisms summed to give an overall total. When entered into a spreadsheet or database, this information can be analyzed to provide details about the blue carbon present in the organisms.

Many questions can be answered from this data. In Figure 2, you can see the answer to two of these questions: How much of the carbon in phytoplankton is eaten by benthos; and how much of the carbon in the seabed gets buried?

Many other questions can be answered using the sampling technique we described, including how much does carbon held by benthos vary within and between sites and how does seabed blue carbon vary between different polar regions? All this information provides a context and understanding of our main area of interest: how does polar blue carbon respond to sea ice losses, and what does this mean for blue carbon's power as a negative feedback on climate change?

WHAT ELSE HAVE WE LEARNED?

Work to date has found that blue carbon varies considerably on polar seabeds. Around West Antarctica there is little change in blue carbon over time in some seas, such as the Amundsen Sea, but a lot in others, such as the Weddell Sea [2, 5] (Figure 3). Changes in blue carbon may be caused by wind (Ross Sea), sea ice losses (Scotia Sea) or sea temperatures (South Georgia). The growth of marine animals has increased most over the last decade in shallow waters, where the animals are close to their phytoplankton food

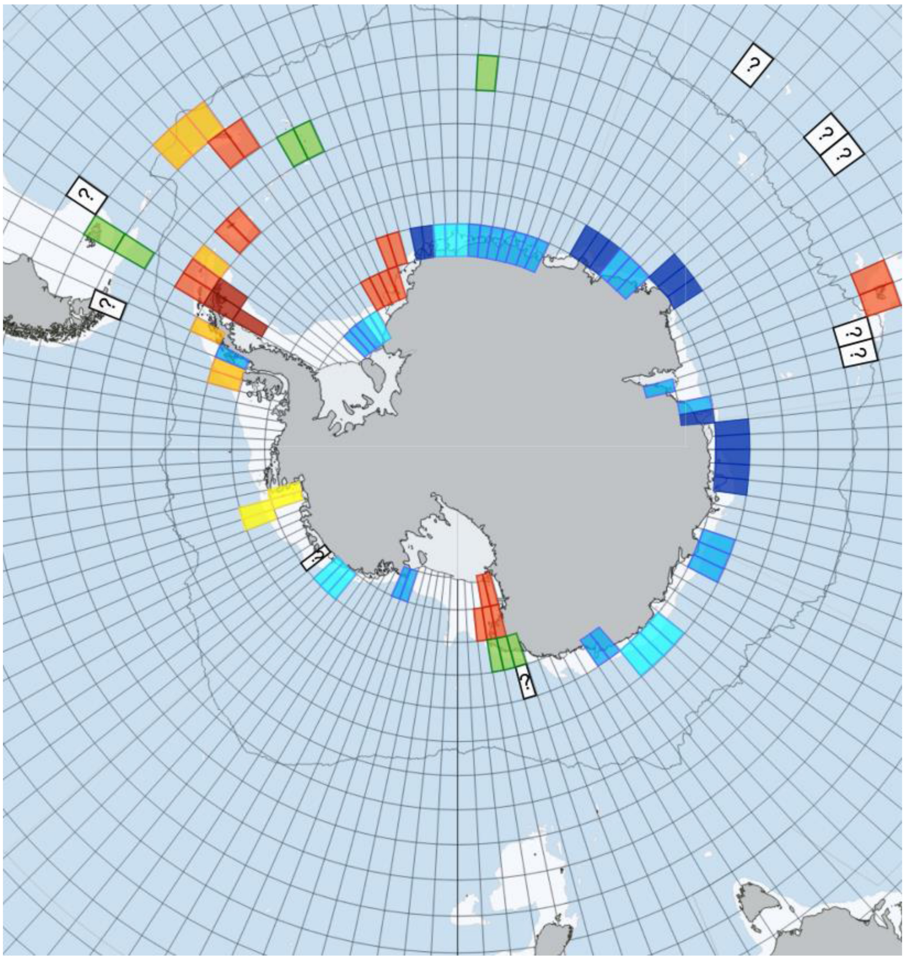

Figure 3

Figure 3

Blue carbon change around Antarctica from 1995 to 2015. Red represents high increase of blue carbon, orange represents moderate increase, yellow represents minor increase, green represents little change in blue carbon and dark blue represents a decrease in blue carbon [5]. Question marks are samples currently under investigation and no information is known for light blue background squares.

[3]. However, iceberg scouring (iceberg collisions with the seabed) has also increased, smashing up the new growth of benthos in the shallows and stopping it from becoming sequestered in the seabed. In deeper water, the growth of benthos has increased less over the last decade, but iceberg scouring is rare below 100 m depth. So although the growth increases of benthos are smaller in deep water than in the shallows, the rarity of deep water iceberg scouring means that these small increases are more likely to eventually be buried and thus sequestered. Giant icebergs breaking off ice shelves are promoting the growth of phytoplankton and helping to increase blue carbon. Creation of a 5,000 km^2 iceberg increases blue carbon by 1 million tons—this is like removing the car exhaust output of 400,000 cars for a year [5]. Understanding blue carbon can help scientists to advise policy makers and politicians how to reduce the amount of atmospheric carbon, which may serve to protect our planet from dangerous climate warming.

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YOUNG REVIEWERS

BUFFALO MUSEUM OF SCIENCE, AGES: 14–18

We are teen scientists who like to learn new things and share them with our community. We are a cool group of people living in Buffalo, NY, and we are the first ever cohort of the Teen STEM Initiative at the Buffalo Museum of Science.

AUTHOR

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David Barnes works for British Antarctic Survey in Cambridge, UK and is a visiting lecturer at Cambridge University. He studies marine life on the seabeds of polar and remote environments, mainly from polar research ships but also by using SCUBA from remote research stations. He is particularly interested in ecosystem services, such as blue carbon, and how these alter with climate change and other human impacts (such as plastic pollution). He currently works on ICEBERGS, ChAOS, Overseas Development Assistance and CoastCarb projects. *dkab@bas.ac.uk

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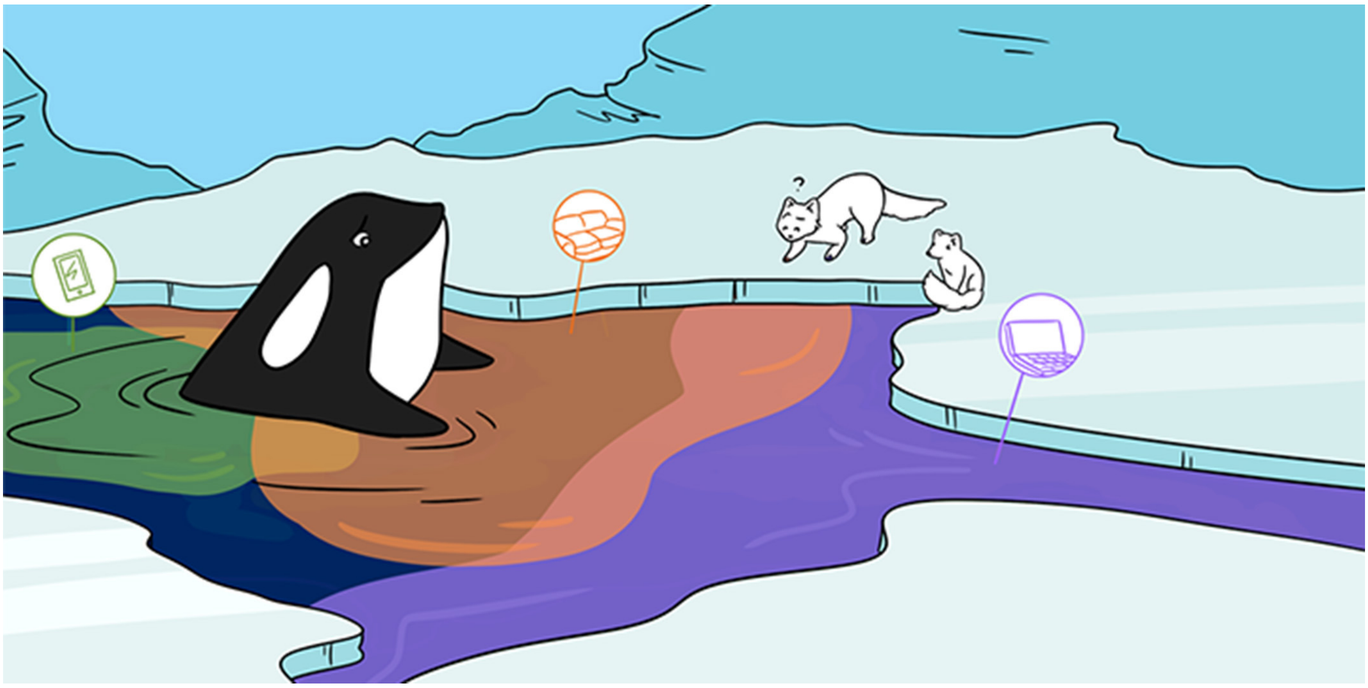

A LONG WAY FROM HOME—INDUSTRIAL CHEMICALS IN THE ARCTIC THAT REALLY SHOULD NOT BE THERE

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YOUNG REVIEWER:

OLI
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It is hard to believe, but some of the chemicals in our couches, computers, and even phones can travel all the way to the Arctic. How is that possible? That is exactly what we were asking when we found chemicals that are used in everyday items—like computers, phones, and couches—in the Canadian Arctic. In this article, we will tell you about our research into these chemicals in the Canadian Arctic and what we found out about their abilities to "fly" and "swim" north to the Arctic. We will also share our ideas on how we can keep animals and people in the Arctic—and around the world—safe from some of these chemicals.

WHAT HAPPENS WHEN CHEMICALS DO NOT STAY WHERE THEY ARE SUPPOSED TO BE?

The chemicals humans make can be fantastic! We can make chemicals that produce any smell, taste, or color we want. Chemicals are what makes medicine help people, chemicals make our cars drive and our planes fly.

Scientists called chemists make many new types of chemicals all the time. Many of these new chemicals are useful, but some can also be a problem. Chemicals are especially a problem if they do not stay where they are supposed to be but leach out from the products to which they are added.

Imagine, for example, a bright red shirt. The red color is great in the shirt, but after you wash it together with a white shirt, you might find that you have a red shirt and a pink shirt instead of a white one (do not try that out at home—your parents might get upset!). What happened? Some of the chemical that makes the red color did not stay where it was supposed to be, in the red shirt, but instead leached out into the water and colored the white shirt.

In the case of differently colored shirts, the leaching of chemicals is just annoying. But now imagine a medicine or a potentially dangerous chemical escaping from where it is supposed to be and entering the water. This chemical might then make animals living in or drinking that water sick.

We know that it can be very bad if large amounts of dangerous chemicals are spilled and reach the environment. But, unfortunately, even small amounts of chemicals can sometimes make animals and people sick.

To protect people and animals from chemicals that can harm them, governments around the world have agreed on ways to judge whether a chemical is too dangerous for use or if it can only be used in specific ways [1]. One of the important criteria to judge if a chemical is potentially dangerous is the time it takes for that chemical to degrade (break down), and finally disappear, in the environment.

Chemicals that **degrade** very slowly are called persistent. Some **persistent chemicals** can stay in the environment for hundreds of years. This means that if a persistent chemical can make a specific type of animal sick, it could continue doing so for a very long time, even for generations.

WHY ARE WE WORRIED ABOUT CHEMICALS IN THE ARCTIC?

The **Arctic** is the high north of our earth. The Arctic is home to polar bears, seals, caribou, Arctic foxes, birds, fish, and people. But not

DEGRADATION

Breakdown of chemicals in the environment. Degradation can happen because of bacteria, water, or even light.

PERSISTENT CHEMICAL

A chemical that does not break down easily in the environment. Some persistent chemicals can stay in the environment for tens and even hundreds of years.

ARCTIC

The high north of our earth, around the North Pole. The Arctic is not one country but several countries are part of the Arctic: Canada, Denmark (Greenland), Finland, Iceland, Norway, Sweden, Russia, and USA. The largest part of the Arctic is not on land but is covered by water—the Arctic Ocean.

many people live there because it is very cold and difficult to get to. There are also very few roads or shops and definitely no factories that produce chemicals.

Even though no chemicals are made in the Arctic, scientists have found many industrial chemicals in Arctic water, snow, air, and even the animals and people living there [2]. Some of these chemicals have been used by, for example, the oil and gas **industry** or military bases in the Arctic. But many of the chemicals the scientists found were not used in the Arctic.

INDUSTRY

All the companies together.

So, the question was, "How do these chemicals get to the Arctic?" Scientists figured out that persistent chemicals can reach the Arctic from where they are made or used by traveling through the water and air.

Here is how these persistent chemicals reach the Arctic. They move more easily and quickly from places where it is warm, which are the places where most people live and where the factories are, but then the chemicals "get stuck" in areas where it is colder. So, persistent chemicals that can travel in water and air move north from where they were made until they get to the Arctic, and then they stay there [3].

This means that the animals and people in the Arctic—who hardly use these chemicals—are in contact with chemicals that could make them sick. Moreover, they do not even have any of the benefits from using the chemicals, or the choice of whether they want these chemicals around or not.

PEOPLE WANTED TO MAKE THINGS BETTER ...

We are interested in certain chemicals called **flame retardants**. Flame retardants are used in many kinds of plastic to make sure they do not burn too easily. Flame retardants are used, for example, in computers, phones, carpets, and the foam in some couches and beds.

FLAME RETARDANTS

Chemicals that are used in a lot of plastic to make sure the plastic does not burn easily.

Unfortunately, many flame retardants that were used in the past, up until about 10 years ago, did not stay where they were supposed to be. Some of the flame retardants got out of the couches, phones, and all the other things they were used in, and got into the air and dust in houses, and then into the outside air and water [4] (Figure 1). The worst part was that these flame retardants were persistent, could reach the Arctic, and were harmful—so they could make people and animals sick [5].

Because of these dangerous properties, some flame retardants are not allowed to be used anymore. But people were still worried that computers, couches, and other plastic things could burn. So, the

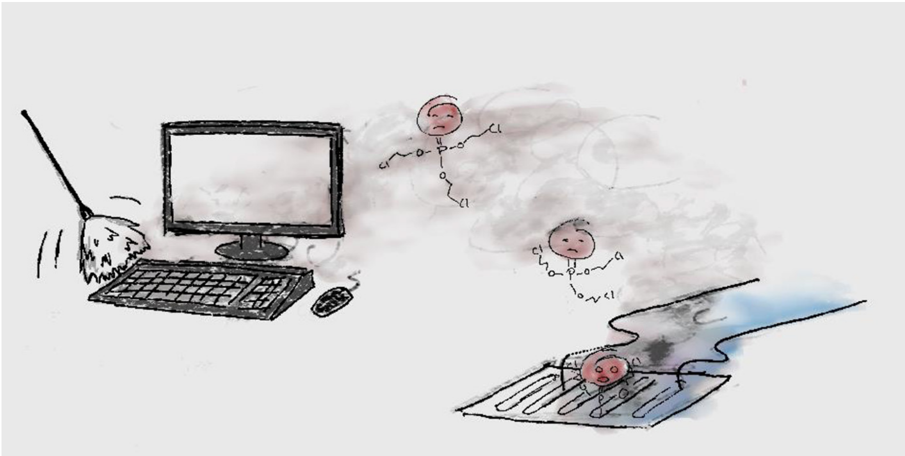

Figure 1

Figure 1

Flame retardants dusted off a computer can get into the environment through the air and rainwater (in this case through the sewers).

chemical industry started using other types of flame retardants, called organophosphate esters, or **OPEs**. The OPEs were not supposed to be persistent or able to get all the way to the Arctic.

OPES

A new type of flame retardant that was supposed to be an environmentally friendly alternative for the old flame retardants that were banned by the government.

Because OPEs are supposed to be an environmentally friendly alternative for the old flame retardants, the industry started using them a lot. But even though they were believed to be more environmentally friendly, OPEs can still make humans and animals sick. Some of them are even suspected to cause cancer [6].

Moreover, when we analyzed air in the Canadian Arctic, we found OPEs. Even worse: we found more OPEs than the old flame retardants that OPEs were replacing [7].

HOW DO OPES GET INTO THE ARCTIC?

We wondered how the OPEs could be getting to the Arctic. Tests had shown that most OPEs were not as persistent as the old flame retardants. Also, computer models had predicted that OPEs would not reach the Arctic [8].

But the measurements were very clear: OPEs are present in the Canadian Arctic.

So, we went back to the Arctic to take more samples to try to figure out how OPEs could make it there.

We took a ship that travels through the Canadian Arctic every summer. We used a pump from the ship to collect air and water samples. We collected samples many times over 7 years, to really make sure we did not miss anything and to find out if the OPEs were always present in the Canadian Arctic or just present sometimes [7].

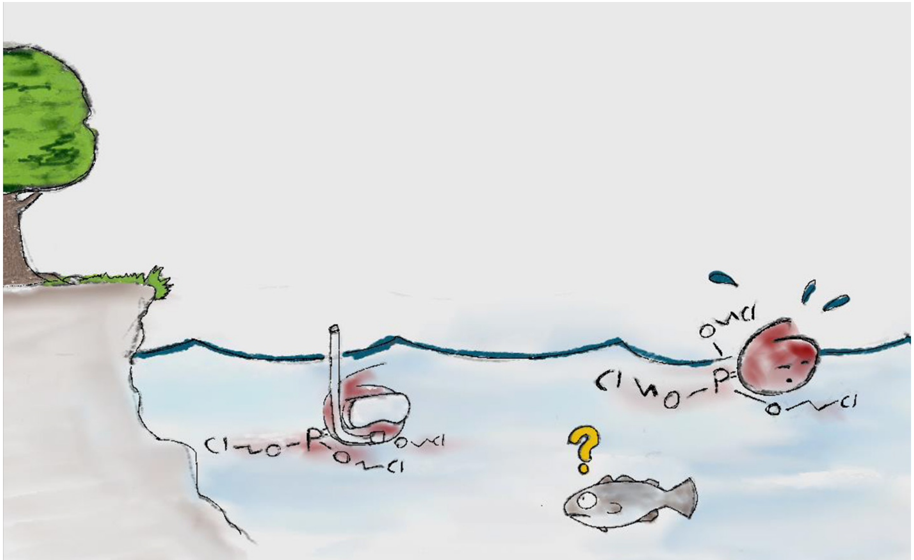

Figure 2

Figure 2

OPEs "swimming" (being transported through the water currents) from somewhere in the south (where they were made) toward the Arctic. In reality, OPEs are very tiny and there are a lot of them, but we had a hard time drawing that.

What we found was that:

- OPEs were found in the Canadian Arctic every time we took samples.
- There are more OPEs in the Canadian Arctic than old flame retardants.
- OPEs seem to get to the Arctic through the air as well as the water [7] (Figure 2).

The idea that OPEs get to the Canadian Arctic through the water was a new result that nobody had really thought about before. This result might explain why so many OPEs are in the Arctic, because OPEs can degrade more quickly in the air than in water. So, if they are in the water, the OPEs could stay there long enough to get to the Arctic [7].

These results meant that OPEs are not a good alternative to the old flame retardants. Instead, just like the old flame retardants, OPEs are persistent enough to also get all the way to the Arctic (Figure 3). In some ways, OPEs are even worse than the old flame retardants, because we find a lot more of them in the Arctic [7].

CAN SOMETHING BE DONE ABOUT THE CHEMICALS IN THE ARCTIC?

Yes, absolutely, something can be done.

The first step is that scientists, regulators, and industry need to check whether we really need all these flame retardants in the first place. Of

Figure 3

Figure 3

OPEs in the Arctic, where they can get stuck in water, ice, and air.

course, nobody wants a computer or couch to burn easily, but some of the flame retardants may actually be worse than not having them because, if they burn, they produce a lot of toxic smoke. Also, other fire protection methods, such as sprinklers and smoke detectors, are much better at preventing fires than flame retardants [5]. So why not use more sprinkler systems and smoke detectors rather than flame retardants that can make animals and people sick?

If there is a case where we really need flame retardants, the industry that produces them should have to prove that the flame retardant they want to use is really less dangerous than the old ones that have been banned.

Very importantly, there are some things every one of us can do:

As adults, we can use our vote! Governments have many decisions to make and deciding which flame retardants are safe maybe is not at the top of the list. But we should all support governments that care about the environment and people's health. This is our great power in a democracy.

Also, no matter what age we are, we can ask people in the shops where we buy plastic toys, phones, tablets, couches, or carpets whether these products have old flame retardants or OPEs in them, and if so, are the flame retardants really needed and do we really need that product? We can demand that the flame-retardant industry tell people if flame retardants are used and which kind are used in a product. This is important because, right now, when you and your parents go out to buy a new phone or couch, you cannot check to see if flame retardants are present in the products you want to buy. If more and more people ask for products without flame retardants, the shops, the industry, and the government will start thinking more about whether flame retardants are really needed in so many products.

Take this one step further and we can ask ourselves if we really need to buy so many new things all the time. Should not a phone, for example, last us longer than just 2 years?

Together, we can work toward limiting the use of dangerous chemicals like flame retardants, to protect the environment and human health.

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ORIGINAL SOURCE ARTICLE

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

OLI, AGE: 13
Oli is a keen guitar player who enjoys speaking Mandarin and playing computer games.

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I am a post-doctoral researcher at Stockholm University. My research is about how chemicals used in everyday products can get into the environment and what happens once the chemicals get there. I am looking, for example, at whether chemicals used as perfumes in soaps can get into fish and if that is a problem for the fish. If I am not doing research I love to dance, travel, hike, or just cuddle up with my husband and son, and read a fun book. *roxana.samson@aces.su.se.

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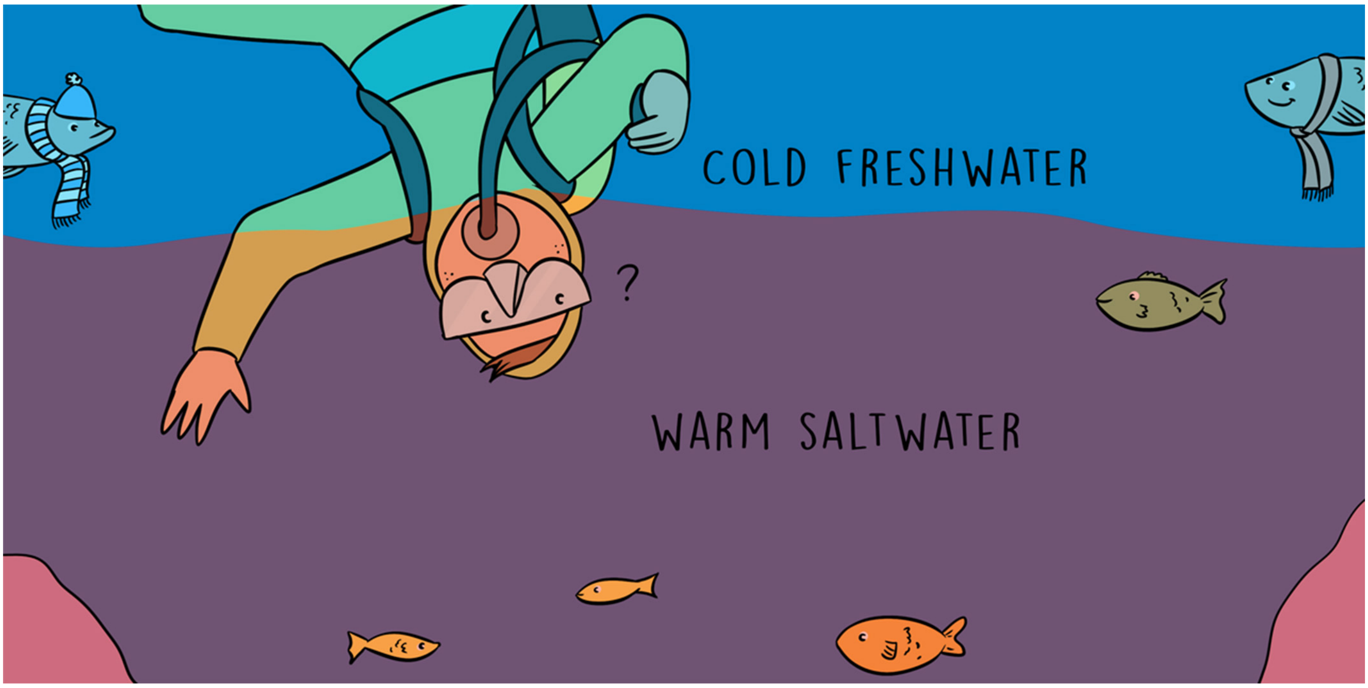

THE ARCTIC: AN UPSIDE-DOWN OCEAN

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YOUNG REVIEWERS:
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The Arctic Ocean is located at the North Pole, sometimes considered the top of the world. Yet this ocean has been called an "upside-down" ocean by famous oceanographer Fridtjof Nansen. Around most of the globe, the surface ocean is warmed by the sun and loses freshwater through evaporation, making it warmer and saltier than the waters below. In the Arctic, cold, fresh water lies above warmer, saltier water that comes from the Pacific and Atlantic Oceans. We explain why the Arctic Ocean waters are layered in this way, how climate change is affecting these layers, and why it matters to us all.

WHY THE ARCTIC OCEAN IS UPSIDE-DOWN

The oceans cover 70% of the globe and most of this water is found at latitudes where it receives sunshine all year around. All this sunshine warms the surface ocean and also drives evaporation which removes **freshwater** from the ocean's surface, leaving behind the sea salts. This means that, in most oceans, we expect to find warm, salty water at the surface, while deeper water tends to be cooler and less salty. So, when the Norwegian explorer Fridtjof Nansen froze his ship *Fram*,

FRESHWATER
Water that has no salt in it. Rivers, rain, snow, and melted sea ice are the key sources of freshwater in the Arctic.

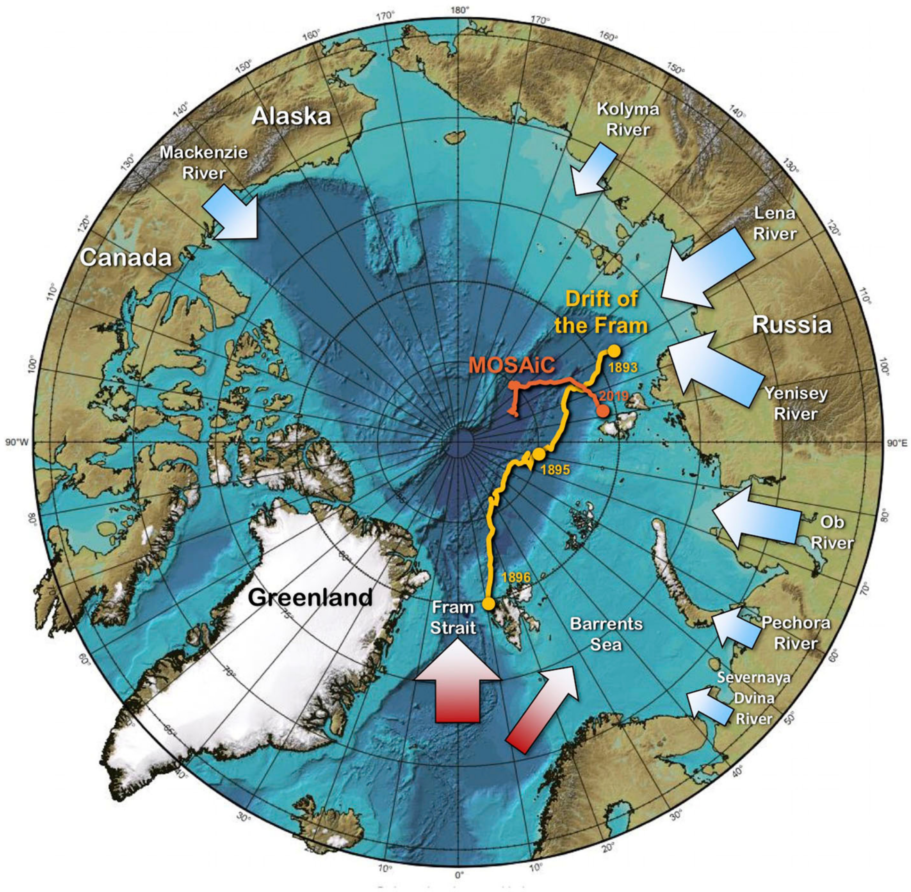

Figure 1

Figure 1

Map of the Arctic Ocean showing the drift of the Nansen's ship *Fram* during his expedition traced in yellow. Blue arrows showthe major sources of cold, fresh water from Arctic rivers, while red arrows show the sources of warm, salty Atlantic water through the Fram Strait and Barents Sea opening. The drift track of the MOSAIC expedition aboard the Polarstern is shown in orange, note that the Polarstern left the ice pack for a crew changeover in June 2020 in Svalbard and will returns to ice pack to continue the drift. Sea floor depth map courtesy of IBCAO [2].

into the Arctic ice, in 1893–1896 (Figure 1) and found cold, fresh water at the surface with warmer, saltier water below, he described the Arctic as an "upside-down" ocean [1]. This early observation of the Arctic Ocean's water structure has been confirmed by numerous oceanographers since Nansen's discovery. Nansen knew that the Arctic Ocean was covered by sea ice, and that the direction the sea ice was drifting could carry his expedition from Siberia, across the North Pole, and back toward Norway. While they missed the Pole by only a few hundred kilometers, the expedition generated a wealth of new findings and provided important knowledge for modern-day Arctic Ocean science.

Since Nansen's time, the Arctic has experienced climate change at twice the rate experienced by other areas of the earth, and the Arctic Ocean has lost a lot of old sea ice. Climate change in the Arctic does not only affect the sea ice. Warming temperatures also affect the water that lies below the ice surface. The MOSAiC expedition, which stands for Multidisciplinary Drifting Observatory for the Study of Arctic Climate, was launched in October 2019 and will hopefully provide some answers about how climate change is affecting the modern-day Arctic sea ice, the Arctic ocean, and the Arctic ecosystem. Today, in

June 2020, the MOSAiC expedition is 7 months into its campaign to follow Nansen's intended path (Figure 1)[1] In the meantime, to understand how climate change might affect the Arctic Ocean, we must consider why there are layers of different water types (or water masses) in the Arctic Ocean and think about where they came from.

[1] https://follow.mosaic-expedition.org/.

THE STRUCTURE OF THE ARCTIC OCEAN

The **density** of seawater depends on both its salt concentration, or **salinity**, and its temperature. As water temperature increases, the water expands and its density decreases, making it lighter. Dissolved salts add mass to the water and increase its density. In warmer waters, which make up most of the world's oceans, the temperature effect on density is more important that the salt effect. So, you will typically find warm water overlying colder water, regardless of the water's salinity.

In cold waters, such as those of the Arctic Ocean, the salt effect on density dominates over temperature. In the Arctic Ocean, you will find cold, fresh water at the surface. This freshwater comes from melting sea ice and from Arctic rivers that empty into the ocean (Figure 2). Below the very cold, fresh surface layer is saltier, denser, but warmer water that has come from the Pacific or Atlantic Oceans. When these warm, salty water masses mix with the cold, fresh surface layer above, they form an intermediate layer known as the Arctic **halocline** (Figure 2). This halocline layer acts as a barrier to heat transfer, preventing the warm, deep waters from melting the sea ice. Below the warmer, saltier water layer, the Arctic Ocean is filled with a slightly saltier, cold water mass, known as Arctic deep water.

WHERE DOES ARCTIC OCEAN WATER COME FROM?

Arctic rivers are the major source of freshwater flowing into the Arctic Ocean. There is so much freshwater run-off from Arctic rivers that the Arctic Ocean is the freshest of all the global ocean basins. Fresh river water is spread through the ocean by winds, tides, and ocean currents, with a lot of freshwater ending up piled at the surface in the middle of the Canada Basin. Some of the river water mixes with saltier seawater in the shallow coastal seas, gains density and ends up in the Arctic halocline, rather than at the ocean surface.

Another source of freshwater for the central Arctic basins is the very low salinity sea ice that drifts over from the shallow coastal seas where it is formed. When sea ice forms, ice crystals form from seawater and most of the salt is rejected as a dense **brine**. The dense brine sinks through the ocean water and eventually slips down the continental slope to fill the deep Arctic Ocean.

DENSITY

The ratio of a substance's mass to its volume. A cubic meter of dense water mass will be heavier than a cubic meter of less dense water. So density of water masses will determine which water mass is found at the surface and which is found at the bottom.

SALINITY

Concentration of salt in seawater. This is usually measured in grams per kilogram. So a salinity of 35 means that in a kilogram of seawater, there are 35 grams of salts.

HALOCLINE

Sub-surface layer of water partially formed through the mixing of the cold fresh Arctic surface waters above it, and the warmer saltier Atlantic or Pacific waters below it. Salinity increases steeply from the top to the bottom of the halocline.

BRINE

A solution of very salty water. Some canned fish comes stored in brine.

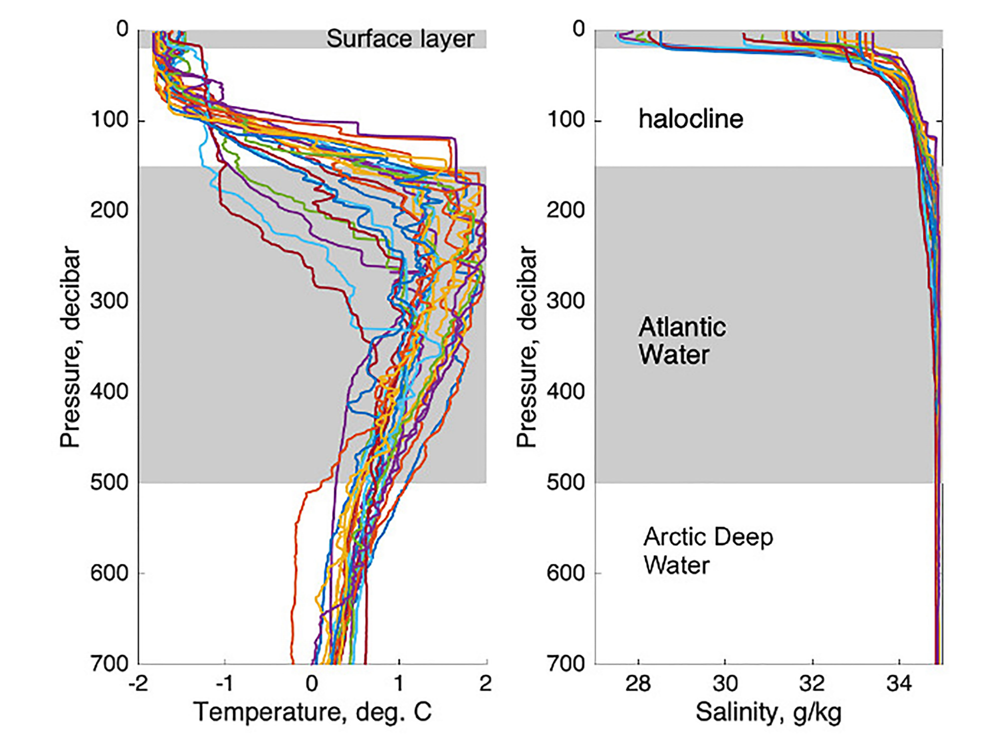

Figure 2

Figure 2

Measurements of water temperature and salinity in the upper 700 m of the Arctic Ocean, taken in October 2008 north of Siberia. The different layers of water are shown with alternating white and gray shading. You can see that the surface layer is very cold and fresh, while both temperature and salinity increase across the halocline below. Atlantic water is easy to spot as the warmest water layer (big bulge to the right) and bottom layer of Arctic deep water is cooler again, and marginally saltier.

The warmest water in the Arctic comes from the Atlantic Ocean. Atlantic water enters the Arctic through Fram Strait, between Greenland and Svalbard, as well as through the Barents Sea Opening, between Svalbard and mainland Norway (Figure 1). Due to the rotation of the earth, Atlantic water moves to the right after leaving Fram Strait, and follows the continental slope around the Arctic in a counter-clockwise manner. When warm, salty Atlantic water first enters the Arctic Ocean through Fram Strait it is near the surface, but it rapidly sinks below the lighter, fresh, cold Arctic surface waters as it flows east. Slightly fresher warm Pacific water joins this counter-clockwise circulation when it enters the Arctic through the Bering Strait. The Pacific water settles just above the Atlantic water.

THE ARCTIC OCEAN INFLUENCES GLOBAL CLIMATE

As the Pacific and Atlantic waters circulate around the Arctic, they mix with the other Arctic water masses becoming cold and fresher, and lose more heat to the sea ice, and the atmosphere above. Water from the Arctic Ocean eventually exits the Arctic through the Canadian Archipelago, or as a deep, cold, fresh current in the western Fram Strait. In this way, the ocean carries solar energy absorbed as heat in the tropics and subtropics, to the Arctic where it acts as a heat source for northern hemisphere weather. Furthermore, the dense deep Arctic outflow water is replaced by the surface inflow of Atlantic and Pacific

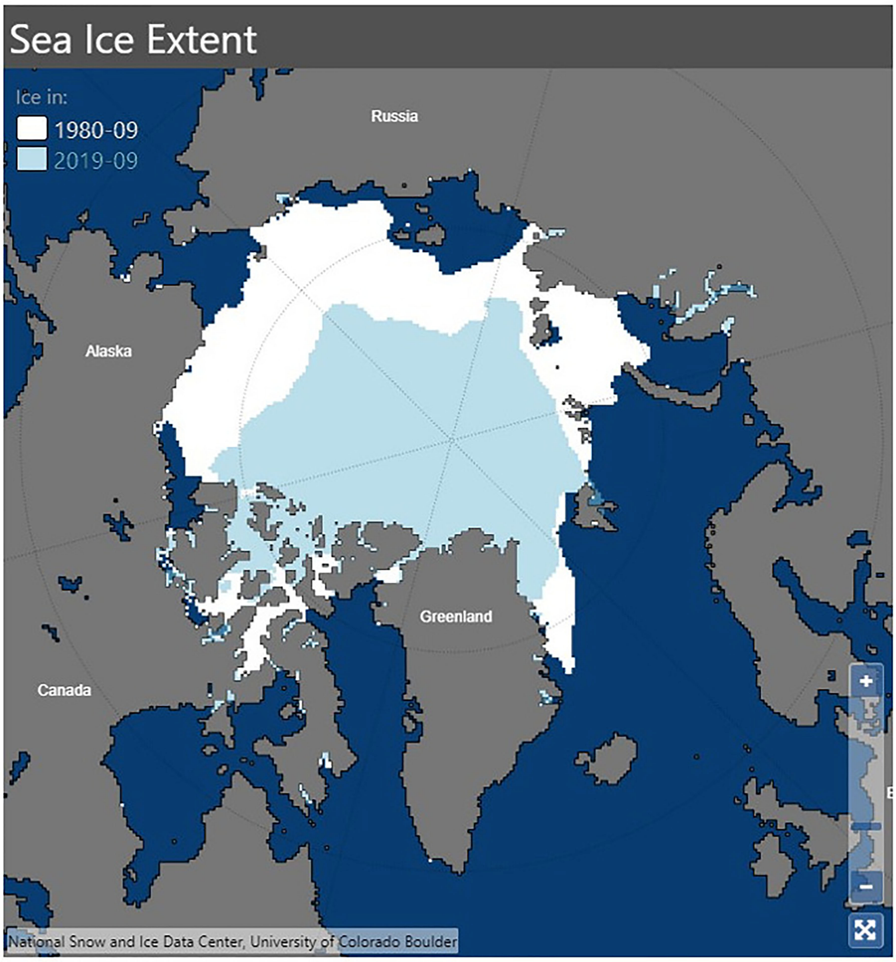

Figure 3

Figure 3

Map of the Arctic Ocean showing the average area covered by summer sea ice in September 1980 (white) and September 2019 (blue). There has been a massive decline in summer sea-ice extent over the last 40 years (Image courtesy of the National Snow and Ice Data Centre, University of Colorado Boulder).

waters ensuring that this exchange between the tropics and polar latitudes continues like a giant conveyor belt.

CLIMATE CHANGE IMPACTS THE ARCTIC OCEAN, ITS ICE, AND ITS ECOSYSTEMS

MULTI-YEAR ICE

This is sea ice that has not melted during summer and has lasted for several years, getting thicker every winter.

Satellite measurements over the last few decades have shown that Arctic sea ice has experienced a steep decline (Figure 3) [3]. New sea ice forms every winter, but in recent years, the melt season has arrived earlier and lasted longer. This increased melt has shrunk the sea-ice coverage as measured in September which is the time of year with the least ice. As the extent of sea ice has decreased, the ice has also lost thickness, as the older, **multi-year ice** has melted or been blown out of the Arctic through Fram Strait.

Recent research shows us that there are multiple causes of sea-ice loss. Because ice is white, it reflects a lot more of the sun's energy back out into space, as compared with the darker, ice-free water, which absorbs solar energy. Therefore, as more water is exposed by sea-ice melt, more heat is stored in the ocean. This extra stored heat then further melts the ice, creating a dangerous cycle of warming [4].

More open water also means greater areas over which the wind can mix up the different ocean layers. This mixing may allow more of the subsurface Atlantic/Pacific heat to reach the ocean surface. At the same time, the temperature of the inflowing Atlantic water has been rising, and the ocean is carrying more heat northward. In summary, there is more heat arriving in or absorbed by the Arctic Ocean, creating more opportunities to bring that heat in contact with the sea ice.

Disappearing sea ice results in larger areas of seawater, where the ocean and atmosphere can exchange heat and freshwater directly. Since the seawater temperature is typically warmer than the air, the ocean is an increasingly important source of heat for the atmosphere. Air temperatures near warm ocean waters have been seen to increase in response to rising ocean temperatures. Disappearing sea ice also means more light penetrates the ocean for longer periods, providing more energy for **photosynthesis** by sea-ice algae and tiny plant-like organisms called **phytoplankton**. Satellite measurements have seen increases in these organisms at the base of all Arctic Ocean food chains [5]. As ocean conditions change in the Arctic, we have also seen a change in the phytoplankton species living there, with an increase in smaller species that thrive in the nutrient-rich conditions caused by the mixing of Pacific and Atlantic waters with the Arctic water [6].

PHOTOSYNTHESIS

A sunlight-powered chemical reaction between water and carbon dioxide that produces sugars and oxygen. This reaction is carried out by plants and plant-like organisms to make fuel to support life.

PHYTOPLANKTON

Tiny microscopic organisms than can photosynthesis like plants. There are many types of phytoplankton including some bacteria and some single-celled plant-like organisms, many of which can form shell-like exoskeletons.

WHY DOES ALL OF THIS THIS MATTER?

From reading this article, you now know that the very cold temperatures and lots of freshwater make the Arctic Ocean an unusual upside-down ocean. These low temperatures mean that solar energy absorbed gained by the ocean in the tropics and carried north is lost in the Arctic, providing heat to the northern hemisphere climate. As the Arctic experiences global warming, the sea ice is melting and the numbers and types of organisms living in the Arctic Ocean may change impacting every part of the food web. Sea-ice loss is beginning to affect ice-dependent hunters, such as polar bears, seals, and walruses. Fish species from warmer waters are also migrating to the Arctic in increasing numbers, because the Arctic Ocean is warming up. Scientists should continue to study how the changes in the Arctic affect marine life and our global climate because these changes will impact many people far beyond the Arctic circle.

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YOUNG REVIEWERS

DEVONPORT HIGH SCHOOL FOR GIRLS (YR 9/2020), AGES: 13–14

We are a group of enthusiastic Year 9 students that volunteered to review the paper because of our interest in science. We enjoyed learning about how science and the review process for scientific papers works from our Science Mentor, Dr. Chapman. We are: Aneura, Anya, Victoria, Izzy, Tanzeena, Daisy, Rowan, Martha, Charlotte, Imogen, and Naomi.

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I am a scientist who studies how different layers of the ocean can move heat and salt around the planet, how these layers mix with each other in the polar oceans and where the energy for mixing comes from. I also teach oceanography at Bangor University in Wales, UK and enjoy hosting visiting schoolchildren who want to know more about the marine sciences. My own children (age 7 and 9) are sometimes forced to help me plan and practice new experiments and demonstrations for these visits. *y.lenn@bangor.ac.uk

BENJAMIN LINCOLN

I am a scientist at Bangor University who makes measurements in the ocean to understand how the wind and tides generate ocean currents, turbulence and mixing. I use these measurements answer questions, such as; What supplies nutrients for plankton and fish? How does deep warm water melt sea ice; How can we build reliable renewable energy devices in the ocean? To make these measurements I go to sea on large research vessels, such as icebreakers. If I am lucky there is 24 h daylight and amazing marine life, if I am unlucky it is, there is 24 h darkness and the ocean is a windblown sheet of ice.

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I am an oceanographer and work in a Polar Research Center in Germany to study the water masses and currents in the Arctic Ocean as well as in the ocean around Antarctica. I often join icebreaker expeditions to study how the polar oceans change and how this impacts the ecosystem and the animals that live on the sea ice and in the ocean beneath.

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