Frontiers for Young Minds

The Ocean, Volume 4

Edited by
Hervé Claustre, Carolyn Scheurle, Laura Lorenzoni,
Sanae Chiba and Emily King

ISSN 2296-6846
ISBN 978-2-8325-2285-1
DOI 10.3389/978-2-8325-2285-1

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

About Frontiers for Young Minds

Frontiers for Young Minds believes that the best way to make cutting-edge science discoveries available to younger audiences is to enable young people and scientists to work together to create articles that are both accurate and exciting. That is why distinguished scientists are invited to write about their cutting-edge discoveries in a language that is accessible for young readers, and it is then up to the kids themselves – with the help of a science mentor – to provide feedback and explain to the authors how to best improve the articles before publication. As a result, Frontiers for Young Minds provides a collection of freely available scientific articles by distinguished scientists that are shaped for younger audiences by the input of their own young peers.

What are Frontiers for Young Minds Collections?

A Collection is a series of articles published on a single theme of research and curated by experts in the field. By offering a more comprehensive coverage of perspectives and results around an important subject of research, we hope to provide materials that lead to a higher level of understanding of fundamental science. Alternatively, a collection could feature articles by scientists who received special recognition, such as a Nobel Prize. Frontiers for Young Minds Collections will offer our international community of Young Minds access to the latest and most fundamental research; and, most importantly, empowering kids to have their say in how it reaches their peers and the wider public. Every article is peer reviewed according to the Frontiers for Young Minds principles. Find out more on how to host your own Frontiers for Young Minds Collection or contribute to one as an author by contacting the Frontiers Editorial Office: kids@frontiersin.org

The Ocean, Volume 4

Collection editors
Hervé Claustre — Centre National de la Recherche Scientifique (CNRS), France
Carolyn Scheurle — Institut de la Mer de Villefranche (IMEV), France
Laura Lorenzoni — National Aeronautics and Space Administration (NASA), United States
Sanae Chiba — North Pacific Marine Science Organization, Canada
Emily King — Xiamen University, China

Citation
Claustre, H., Scheurle, C., Lorenzoni, L., Chiba, S., King, E., eds. (2024). *The Ocean, Volume 4.* Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-2285-1

Cover image
FourPlus Studio

Participating sections

Biodiversity

Earth and its Resources

About this collection

The ocean allowed life to develop on earth billions of years ago, it is vital for all of us and it will guarantee the future of humanity. The ocean is vast, deep, harsh and somehow "rebellious" to reveal its secrets and hence, there is much that is unexplored and not yet understood.

Scientists need to study the ocean to better understand its functioning, its properties, as well as how it shapes our environment and impacts us. For example, do you know what the role of the ocean is on weather and climate? There also remains so much to explore and investigate as diverse oceanic resources (fish stocks, bio-molecules, renewable energies but also minerals, oil and gas...). How can we make sure that our use of these resources is respectfully done and sustainable and how can we minimize our impacts (e.g. pollution, acidification, deoxygenation) on the ocean as our human population increases?

In this Collection of Frontiers for Young Minds, ocean scientists from various disciplines explain recent discoveries or fundamental concepts. They share their knowledge and motivations and give insights into innovative tools and methods used to better understand our ocean. The Collection targets a large range of oceanic environments from the open ocean to the shores, the surface to the abysses including specific areas like coral reefs. It also targets the connections of the ocean with its interfaces (atmosphere, ice, coast). It seeks to cover marine disciplines that range from physics to chemistry, from biology and genomics to biodiversity and ecology, and from economy to conservation and policies. Finally, it encompasses a great variety of scales, ranging from the diel to geological time-scales, from loco-regional to global scales and also from the tiniest cells to the biggest living animals on our planet.

The United Nations have declared the 2021-2030 period as the "Decade of Ocean Science for Sustainable Development", stressing the urgent need to approach fundamental issues related to the ocean and the future of humanity on well sounded scientific grounds and knowledge. The oceanic sciences are indeed undertaking a revolution thanks, in particular, to robotization and the massive intrusion of big data and artificial intelligence. This Ocean Collection aims to accompany this evolution to provide information to young readers that will help them to increase their understanding of the ocean and its central role in nature and our lives. We hope to empower them to make informed decisions in these challenging times and to engage to protect, study and enjoy its richness.

See here our previous Volumes: Volume 1, Volume 2 and Volume 3!

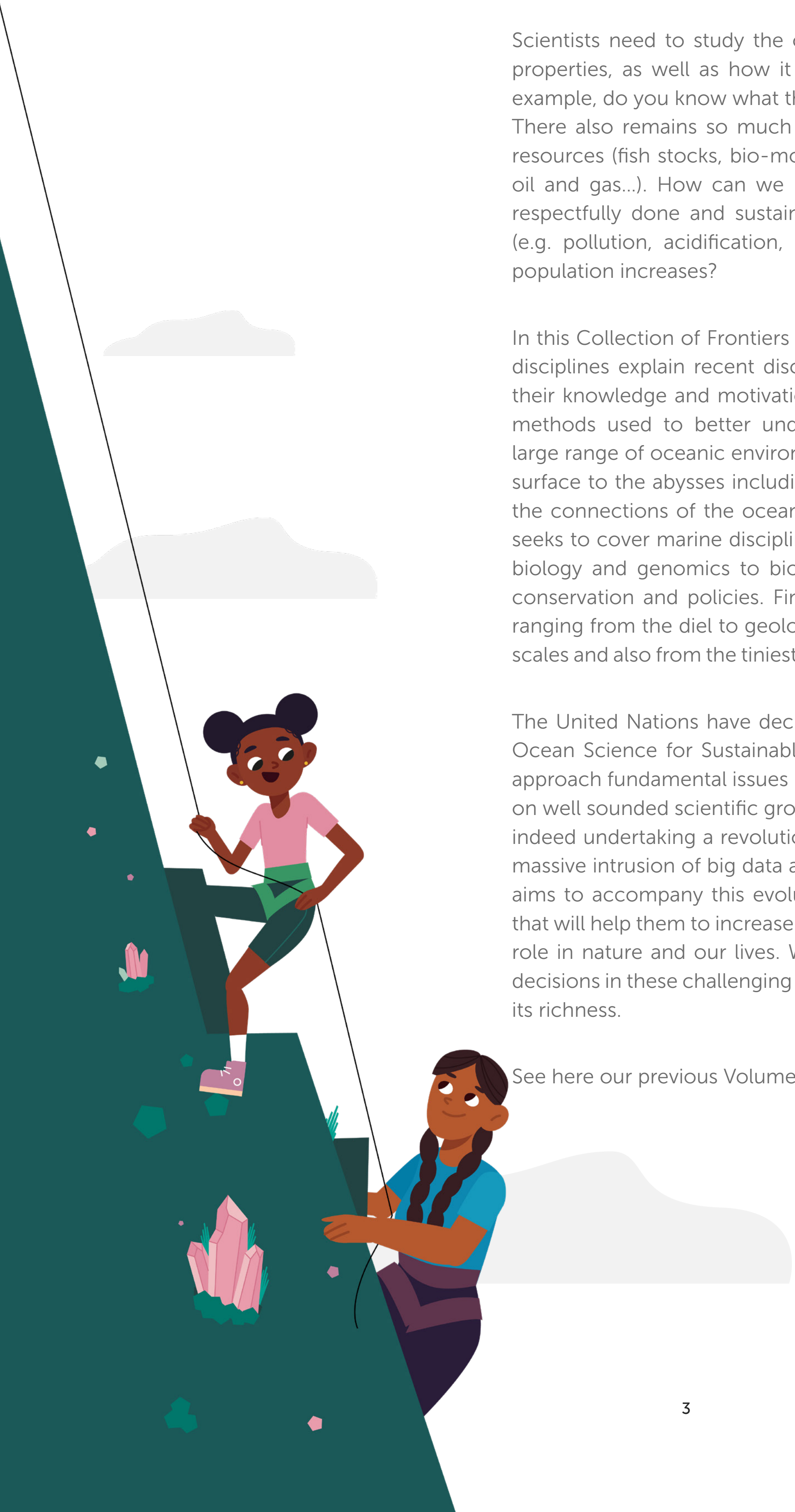


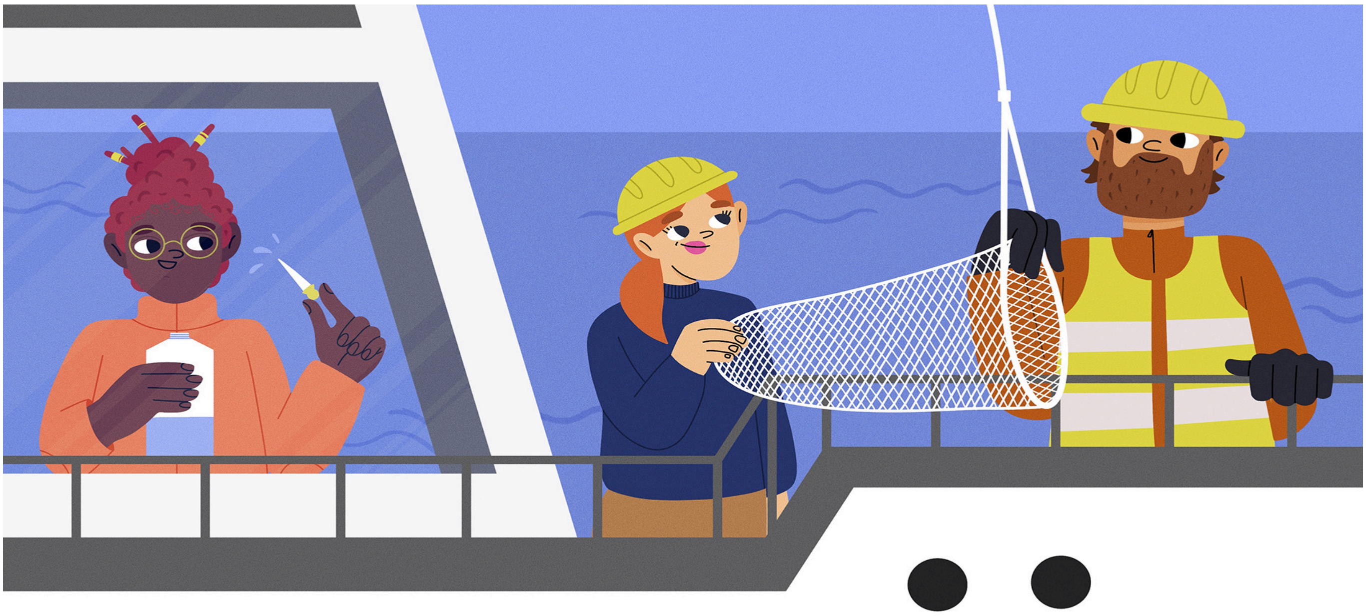
Table of contents

Table of contents

Table of contents

frontiers | Frontiers for Young Minds

BIODIVERSITY
Published: 25 January 2024
doi: 10.3389/frym.2023.1184073



ALL ABOARD! BEHIND THE SCENES OF A SCIENTIFIC RESEARCH CRUISE

Tricia Light[1], Emmet Norris[1], Dongran Zhai[2], Ruth Varner[1], Kaycie B. Lanpher[1], Dante Capone[1], Natalia G. Erazo[1] and Richard Norris[1]*

[1] *Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, United States*
[2] *Ocean Sciences Department, University of California, Santa Cruz, Santa Cruz, CA, United States*

YOUNG REVIEWERS:

ERIC
AGE: 10

GEMMA
AGE: 8

From our climate to the air we breathe, the ocean influences the world around us. Scientists are always looking for new ways to explore and study the ocean. One way we do this is by going on specially designed ships that allow us to study the deep sea, far from land. On our latest expedition aboard the Research Vessel Sally Ride, we went out 300 miles into the North Pacific Ocean for a week. We used some of the most important ocean science tools to catch tiny marine animals, collect water from some of the deepest depths, uncover mysteries of oceans past, and study how desert dust feeds marine animals today.

WHY DO SCIENTISTS GO ON RESEARCH CRUISES?

When we think about the ocean, most of us think of crashing waves and animals like whales and dolphins. The ocean covers 70% of our planet's surface and is incredibly important to the Earth and human life. It helps determine our weather and **climate**, and it absorbs some of the gasses that cause climate change [1]. Fish from the ocean feed billions of people every day [2]. We rely on the ocean for so much that it is important to understand how it works and how humans are changing it. Scientists have lots of tools for studying the ocean. We can use satellites to look at the ocean from space, and we can study the ocean from the coast. These methods give us a good idea about the ocean's edges, but we also need ways to study the deep ocean, far away from land. To do so, scientists go to sea on specially designed ships with science tools for collecting all kinds of information. These research expeditions can be days or even months long.

CLIMATE

The weather conditions of a place over a long period of time.

Come aboard our expedition! Here is a look into our voyage on board the Research Vessel Sally Ride in the North Pacific Ocean. You can learn what we did at sea and how we used four important tools to study the ocean: the CTD, the multicorer, the tow, and **aerosol** samplers (Figure 1).

AEROSOL

Small liquid or gas particles suspended in a gas. Here, this gas is air.

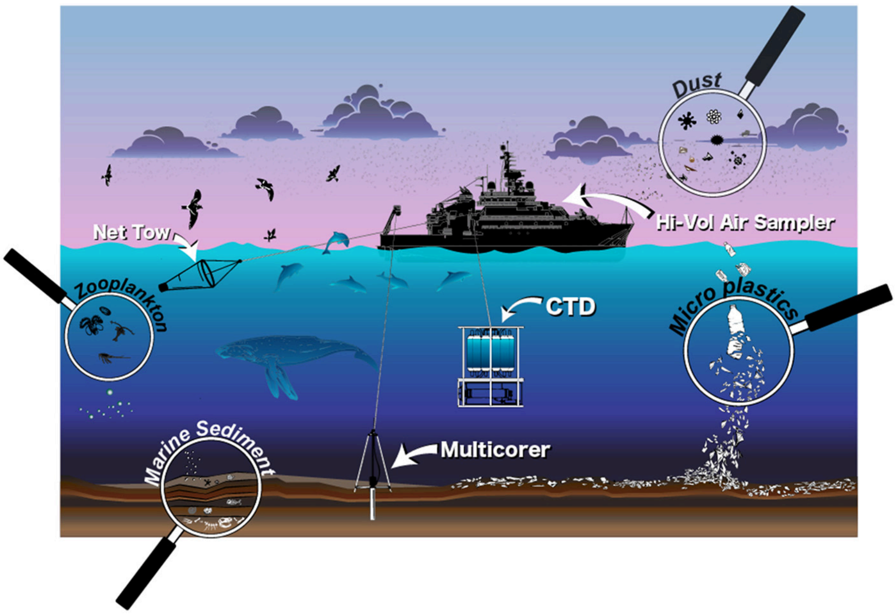


Figure 1

Figure 1

This illustration of our ship at sea shows various parts of the ocean and how we use our equipment to study them. It shows a net tow dragging through the water, a multicorer collecting marine sediment (or mud), a CTD collecting seawater, and a Hi-Vol air sampler collecting aerosols at the front of the ship. The ship is about 73 m (238 feet) long. Take a virtual tour of the ship here, and visit this site to learn more about our day-to-day activities on the ship.

THE CTD: DIVING INTO THE DEEP OCEAN

The CTD is named after three things it measures. "C" is for **conductivity** (how salty seawater is), "T" is for temperature (how hot or cold seawater is), and "D" is for depth (how deep the CTD has sunk). A CTD is shaped like a giant can with lots of smaller tubes inside it. It carries water samplers and electronic sensors [3]. We lower the CTD off the side of the ship, and as it sinks, it collects both samples and information (Figure 2A). We can also add more tools to the CTD to measure things like how much sunlight there is, how many living things there are, and

CONDUCTIVITY

How easy it is for electricity to pass through a material. In the ocean, we use conductivity to measure how salty seawater is.

how cloudy the water is. All this information is sent back up to the ship for the scientists to use.

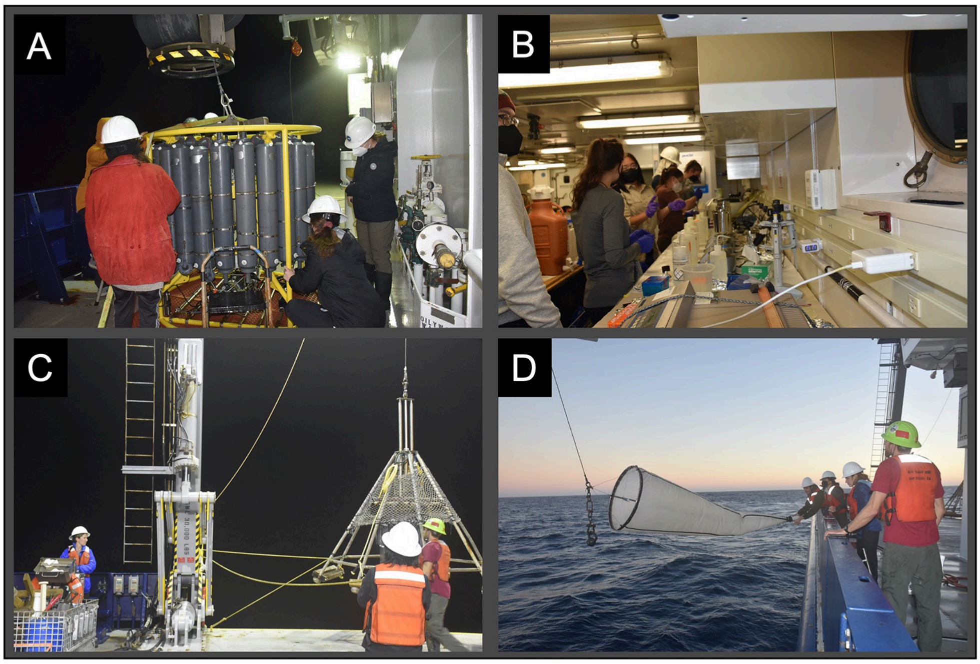


Figure 2

Figure 2

Science at sea. **(A)** Scientists prepare the CTD to collect seawater. **(B)** Kaycie leads a team collecting microbes from seawater. **(C)** Cate uses a multicorer to collect deep sea mud. **(D)** Annie sends out the net tow to sample plankton.

The water samplers are bottles that can be opened and closed deep in the ocean using electronics on the ship. The water samples allow us to measure what makes up ocean water and what lives in it. By filtering the water, we can look at particles of dust, DNA and nutrients (Figure 2B). Just for fun, we decorated styrofoam and sent it down to the deep ocean on the CTD! The weight of the ocean above it squeezed all of the air out of the styrofoam and made it a lot smaller (Figures 3A,B).

We use information from the CTD to answer important questions about what happens in the ocean. On our cruise, Linqing used water from the CTD to explore how ocean water moves around. Tricia used the CTD to look at how food is recycled in the ocean (Figure 3C). Kaycie used the CTD to study how **microbes**, or tiny organisms, get energy from the food they eat. We sent the CTD down more than 4,500 m (14,764 feet) below the ocean's surface.

MICROBES

Living things that are too small to see with just your eyes.

CORING: COLLECTING DEEP OCEAN MUD

We have a time machine aboard. It does not carry us physically into the past, but we can use it to see what Earth was like long ago. Our time machine is a multicorer (Figure 2C). It collects mud from the seafloor that accumulated over the past centuries of ocean history [4]. The seafloor is constantly being rained on by mud carried into

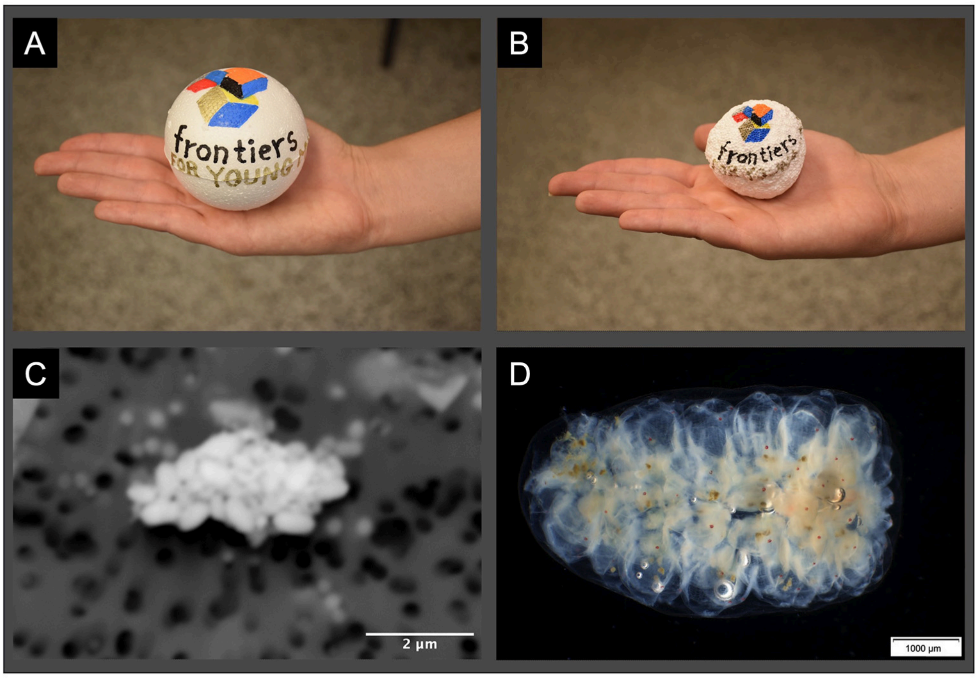


Figure 3

Figure 3

Some of the fun things scientists see at sea. A styrofoam ball **(A)** before and **(B)** after it is sent down to the deep ocean on the CTD. The ball shrank to about 2/3 of its original size because of the enormous pressure created by the weight of the ocean above it. **(C)** A microscope image of crystals that form in dead organisms as they are broken down in the ocean. **(D)** A microscope image of a pyrosome, or a type of squishy zooplankton, captured by a net tow. Scale bars for **(C)** and **(D)** are in micrometers (μm; 1/1,000 of a mm or about 1/70 the width of an average human hair).

the sea by rivers, dust, pollen, and ash blown from land, and dead organisms that sink from the sea surface. All this stuff settles on the ocean bottom every hour of every day. As the centuries pass, the layers of mud thicken, preserving the history of fires, floods, and land life swept into the sea. The mud obtained by the multicorer tells the story of Earth's past.

How does the multicorer work? It looks like a moon lander with four legs supporting a triangular structure attached to the ship with a cable. Heavy weights slowly shove eight plastic tubes into the seabed. The device is then hauled back to the ship with a cable. Each tube is sealed by spring-loaded doors to preserve the mud inside. The tubes of mud are called cores.

The layers in the cores capture information about how humans are changing the world. Looking back at what Earth was like long ago helps us predict how the Earth might change in the future. On our cruise, Cate is using cores to find out how much of the plastic that humans throw away ends up on the seafloor. She will compare the mud now to mud from decades ago, to see how it has changed. The cores are like a fat book of Earth's history—a time machine to our past.

ZOOPLANKTON

A category of ocean animals that mostly drift along with ocean currents. Zooplankton include everything from big jellyfish to tiny larvae.

TOWS: CATCHING LITTLE ANIMALS IN OUR NET

We do not care only about ocean mud and ocean water—we also care about ocean life! We use a net tow (Figure 2D) to catch **zooplankton**, which are small ocean animals that mostly drift along with ocean currents [5]. Most zooplankton are so tiny that you need a microscope to see them well (Figure 3D). Some zooplankton, like jellyfish, are bigger. Zooplankton are an important part of the ocean's food web because they get eaten by fish and other animals. Lots of large animals like tuna, squid, and crabs start out as plankton before they get big, while others remain tiny their whole lives.

The tow looks like a net that you might use to catch fish in a stream, but ours is so big that it takes a full team of scientists to use. Its holes are much smaller than a fishing net's holes, so zooplankton will not float through. We hang the tow off the side of the ship into the water. We then move the boat forward, so the tow catches the zooplankton swimming through the water. After a few minutes, we bring the net back to the ship to see what we caught. We have a microscope on the ship to see what the tiny zooplankton look like. We also store some of the zooplankton to study back on land.

We collect zooplankton to answer all sorts of questions: How do plankton change over time? Are large or small plankton more common? What do plankton eat and where does it come from? On our cruise, Annie collected zooplankton to help answer some of these questions. Some of the zooplankton also end up in the Scripps' Collections, where they will sit on shelves like library books alongside samples over 100 years old!

AEROSOL SAMPLING: COLLECTING DUST FROM OCEAN AIR

Did you know that plankton get food from the sky? Although you might not be able to see it, there are billions of tiny pieces of rock floating around in the air all around you [6]. These little particles are called dust. Around 500 million tons of dust fall into the ocean each year, bringing with it nutrients like iron that many organisms, like **phytoplankton**, need to live. This dust comes from all over the world, including the Sahara Desert in Africa and glaciers in Alaska. It floats with the wind until it eventually falls into the ocean, where it can be used by animals. The amount of dust that enters the ocean changes depending on what is happening on land. Dust helps determine how much life is in the ocean, which can affect global climate by adding or removing gasses from our **atmosphere**.

PHYTOPLANKTON

Microscopic organisms that live in water and get their energy from the sun, just like plants do on land.

ATMOSPHERE

The layer of gases that surround our planet.

Onboard the ship, Emmet studied dust by sucking lots of air through a filter that catches the dust. To do this, he used a type of aerosol sampler called a Hi-Vol air sampler. Back on land in his lab, he can learn a lot about this dust. He hopes to learn more about the amazing ways that air transports nutrients around the world, even if we cannot see it with our eyes.

HOW CAN I GO TO SEA?

There are all sorts of ways to become a scientist who goes to sea. The scientists on our cruise are from five different countries. They studied various college subjects—chemistry, biology, physics, anthropology, and even art! Some of them have always wanted to study the ocean, and some did other things before becoming ocean scientists. We all worked really hard and prepared a lot so that we could deal with the challenges of being at sea. Some of the problems we overcame during our cruise were people getting sick, tools breaking, and experiments not working the way we expected. To get a taste of what it is like to be a scientist at sea, explore websites (like this one) about ocean science. You can also get out and explore near where you live, from a park to a stream to a city block. To become a scientist, you need a sense of wonder and you must pay attention to little details, write everything down, and notice changes that happen over time. Above all, have fun!

ACKNOWLEDGMENTS

The authors thank the science party and crew of SR2215 for their invaluable assistance and contributions. Funding for this research cruise was provided by the UC Ship Funds program. Additional funding supporting research completed on this research cruise was provided by the National Sciences Foundation, award number 2126668.

AUTHOR CONTRIBUTIONS

TL, EN, DZ, RV, and RN conceptualized and planned this work. EN and DC created figures. All authors wrote and revised sections of the manuscript.

REFERENCES

1. Bigg, G. R., Jickells, T. D., Liss, P. S., and Osborn, T. J. 2003. The role of the oceans in climate. *Int. J. Climatol.* 23:1127–59. doi: 10.1002/joc.926
2. Food and Agriculture Organization of the United Nations. 2022. *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*. Rome: FAO. doi: 10.4060/cc0461en
3. White, M., Mohn, C., and Kiriakoulakis, K. 2016. "Environmental sampling", in *Biological Sampling in the Deep Sea*, eds M. R. Clark, M. Consalvey, and A. A. Rowden (Hoboken, NJ: John Wiley and Sons), 57–79. doi: 10.1002/9781118332535
4. Tuit, C. B., and Wait, A. D. 2020. A review of marine sediment sampling methods. *Environ. Forensics.* 21:291–309. doi: 10.1080/15275922.2020.1771630
5. Sameoto, D., Wiebe, P., Runge, J., Postel, L., Dunn, J., Miller, C., et al. 2000. "Collecting zooplankton", in *ICES Zooplankton Methodology Manual*, eds R.

Harris, P. Wiebe, J. Lenz, H. R. Skjoldal, and M. Huntler (Cambridge: Academic Press), 55–81. doi: 10.1016/B978-0-12-327645-2.X5000-2
6. Fitzgerald, J. W. 1991. Marine aerosols: a review. *Atmos. Environ. A. Gen. Top.* 25:533–45. doi: 10.1016/0960-1686(91)90050-H

SUBMITTED: 06 April 2023; **ACCEPTED:** 22 December 2023;
PUBLISHED ONLINE: 25 January 2024.

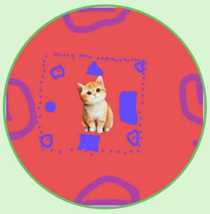
EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Shu Qin Sam and Nancy Lo Man Hung

CITATION: Light T, Norris E, Zhai D, Varner R, Lanpher KB, Capone D, Erazo NG and Norris R (2024) All Aboard! Behind The Scenes Of A Scientific Research Cruise. Front. Young Minds 11:1184073. doi: 10.3389/frym.2023.1184073

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



ERIC, AGE: 10

Hello, my name is Eric, I am Brazilian. I am 10 years old. I am in the fifth grade at school. I like to run, sports (swimming, capoeira, football, biking), to play games, play violin, go to the beach and play with my cat Crystal. Not only that, but I also like space and robots.

GEMMA, AGE: 8

My favorite subject is science and I love almost everything related to the ocean. I am an avid reader of science, mystery, and fantasy books. I read National Geographic Kids and enjoy playing around with their app. I am also interested in Thea and Geronimo Stilton books. I have a special liking for those with jokes and games at the end or the ones that you can help them solve the mystery with the given clues.

AUTHORS

TRICIA LIGHT

Tricia Light is a marine chemist and Ph.D. candidate at the Scripps Institution of Oceanography in San Diego, California. She studies how crystals in seawater and ocean mud can help us understand the relationship between life in the ocean and climate change. In her free time, she loves hiking, swimming, and spending time outside. *tlight@ucsd.edu

EMMET NORRIS

Emmet is a geochemist/artist/community organizer and Ph.D. student at the Scripps Institution of Oceanography, where he studies the intersection of earth science and human health. He is interested in how modern human activities such as agriculture and mining affect natural cycles on the Earth's surface, and how these systems then affect human communities, particularly marginalized communities. He loves cactus flowers and thinking about how magnificent the Earth is.

DONGRAN ZHAI

Dongran Zhai is an oceanic climatologist and Ph.D. candidate at University of California, Santa Cruz. She is working on observing and understanding changes in global ocean chlorophyll over time. She uses observations from satellite ocean color data and simulations from models. She loves cooking and baking!

RUTH VARNER

Ruth Varner is a biological oceanographer and M.S. student at the Scripps Institution of Oceanography in San Diego, California. Ruth is interested in investigating how microbes can influence the growth of organisms in extreme environments. Her current research focuses on the mechanisms that underlie how organisms called halophic archaea interact with microalgae to allow them to grow in some of the world's saltiest environments. In her spare time, she loves reading, running, and exploring the world around her.

KAYCIE B. LANPHER

Kaycie B. Lanpher is a marine microbiologist and chemist at the Scripps Institution of Oceanography at the University of California San Diego. She studies how marine microbes, such as bacteria and phytoplankton, are impacted by the marine environment and control the chemistry of the ocean. She studies these interactions from coastal beaches to the middle of the ocean. She got her Ph.D. in ocean sciences and loves to travel the world, meet new people, and learn about different cultures. When she is not working, Dr. Lanpher enjoys rock climbing, knitting, and playing soccer.

DANTE CAPONE

Dante Capone is a biological oceanography Ph.D. student at the Scripps Institution of Oceanography in San Diego, California. Dante's research explores what plankton can tell us about how the oceans are changing. He is especially interested in how California's recent megafires might be affecting the ecosystem off the coast. Outside of his studies, he runs for the San Diego Track Club Elite group and enjoys making art and sourdough bread.

NATALIA G. ERAZO
Natalia Erazo is a marine microbiologist and Ph.D. candidate at the Scripps Institution of Oceanography in San Diego, California. Natalia studies how microbes are responding to climate change and pollution. She is interested in conservation policy, climate change adaptation and mitigation, and works with women-led fisheries on seafood sustainability and how to better protect marine ecosystems. She loves swimming, diving, and sailing.

RICHARD NORRIS
Richard Norris is a paleontologist at the Scripps Institution of Oceanography in San Diego, California. He is interested in the impact of past environmental change on ocean life. Lately he has been using microscopic fish teeth and bones to understand how the abundance of reef fish keeps corals healthy. The tiny fossils he extracts from ocean mud tell lots of neat stories about how people have changed the world. He enjoys traveling the deserts, looking at birds, and making jam and a warm scone!

frontiers | Frontiers for Young Minds

EARTH SCIENCES
Published: 25 January 2024
doi: 10.3389/frym.2023.1178327

THE SILICON CYCLE IN THE OCEAN

Lucie Cassarino [1*], ***Rebecca A. Pickering*** [2*], ***Zhouling Zhang*** [3] ***and Bianca Liguori*** [4]

[1] *Université de Bretagne Occidental, Institut Universitaire Européen de la Mer, LEMAR Laboratory, Plouzané, France*

[2] *Department of Geology, Lund University, Lund, Sweden*

[3] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany*

[4] *Marine Isotope Geochemistry, Institute for Chemistry and Biology of the Marine Environment (ICBM), University of Oldenburg, Oldenburg, Germany*

YOUNG REVIEWERS:

JASRAH

AGE: 10

The element silicon is everywhere! In fact, silicon is the second most abundant element in Earth's crust. Silicon in rocks and minerals breaks down and is transported from rivers and streams into the world's oceans. Many marine organisms need silicon as it is a crucial nutrient to build their skeletons. Silicon eventually reaches the seafloor, but its journey into the abyss is not straightforward due to biological, physical, and chemical processes. All these processes transport and transform silicon, creating a cycle that we call the marine silicon cycle. The silicon cycle is directly connected to the carbon cycle, making silicon a key player in the regulation of Earth's climate. In this article, we discuss why we need to understand the marine silicon cycle, explain the steps that happen in the ocean, and demonstrate how the marine silicon cycle affects humans.

WHAT IS SILICON AND WHY IS IT IMPORTANT?

Silicon is everywhere you look! It is in the rocks beneath your feet, the plants that help you breathe, in the skeletons of some animals, and even in our own bodies. Therefore, silicon is an essential nutrient that helps support all types of life. You will find silicon in almost every living organism, from bacteria to plants and animals, on land or in the oceans. Among the 118 elements known to exist in the universe, silicon is the seventh most abundant. On Earth, silicon is the second most abundant within Earth's crust—the very upper layer of the Earth that we live on. This means that most of the rocks we see, touch, or sit on have silicon in them. Silicon is also everywhere inside our homes. It is used to build walls and floors, as silicon sand is an important part of concrete. It is a key part of electronics, and it makes up the main ingredient in glass, like the windows that let the sunshine in and the glasses you drink your juice and soda out of (as illustrated in Figure 1).

Figure 1

Figure 1

The element silicon (Si) is everywhere in our surroundings. It is found in the skeletons of organisms, in rocks, and in some manmade materials like glass and concrete. Silicon is critical for humans as well.

Each element on earth, including silicon, moves from the earth crust to the ocean and back to the earth crust, this is what we call the **silicon cycle**. Scientists study the silicon cycle because it tells us about the stability and wellbeing of our planet. Rocks and minerals on land break down over time into smaller pieces. From there, silicon travels in streams and rivers to the oceans, and ends up in the interior of the Earth, creating a cycle that keeps the environment stable. Fossil records (see this article for more info) have shown us that, for millions of years, silicon and carbon have been linked together. But how?

SILICON CYCLE

The transfer of the element silicon from the earth crust, through the rivers and oceans, followed by its burial in the sediment to finally going back in the earth's crust.

ROCK WEATHERING

The process by which rocks, solid, and other materials are broken down and worn away by the effect of wind, water and the other natural forces over time.

SILICATE CARBON SINK

This is the transfer of carbon from the surface of the ocean to the deep layer due to organisms made of silica.

THE MARINE SILICON CYCLE

It represents the loop of the element silicon in the ocean. It describes how silicon enter the ocean, is transformed within the ocean and exits the ocean.

The silicon cycle starts on land, *via* a process called **rock weathering**. Rocks on Earth are naturally broken apart by water from the rain and rivers, or by the wind. A common example is the coastline being destroyed after a big storm passes through, but this process also happens at a smaller scale on land, especially in the mountains. There, water from rain and rivers mixes with rocks made of silicon (called silicate rocks) and creates a chemical reaction that uses up the carbon dioxide (CO_2) in the atmosphere. When the climate is warmer, there is more CO_2 in the air. This makes it easier for CO_2 to react with silicate rocks, which helps to remove CO_2 from the atmosphere. In this way, silicate rocks and rain participate in the natural balance of our climate [1]. This is what we call the **silicate carbon sink** [2]. It helps to balance the amount of carbon in the atmosphere and oceans, and it can help to reduce the effects of human impact on climate change. Weathering is not only important for removing atmospheric CO_2, but it also releases dissolved silicon into the waters flowing into the rivers toward the ocean. This silicon is in a dissolved form (like when you put solid sugar or salt in water and it disappears), making it available as a nutrient for organisms on land and in the oceans.

HOW DOES SILICON GET INTO THE OCEANS AND WHERE DOES IT GO?

Because rivers, streams, and water within the ground eventually flow into the oceans, the dissolved silicon in these waters also ends up in the oceans. This is also where a new part of the silicon cycle begins—the **marine silicon cycle** (Figure 2). Silicon eventually makes

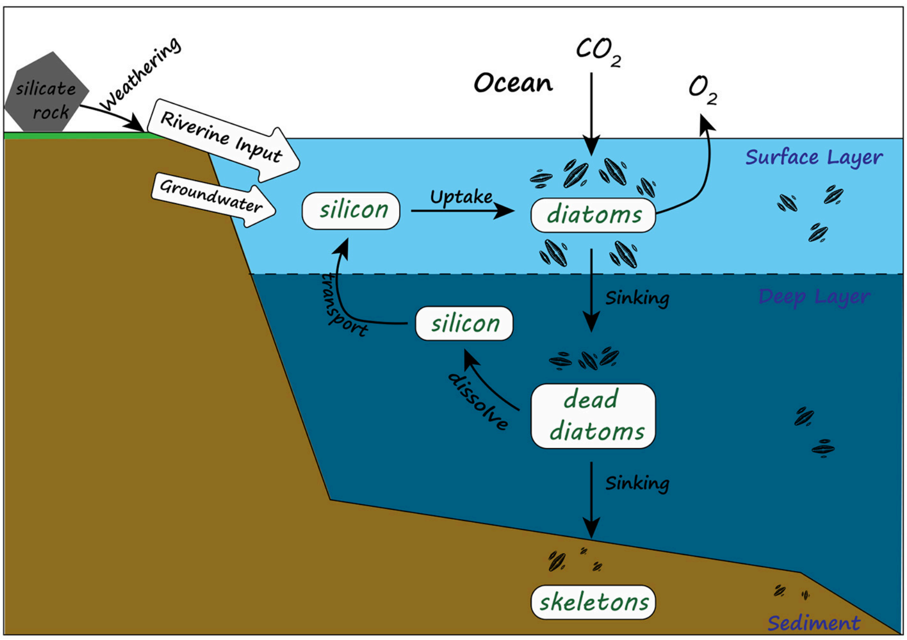


Figure 2

Figure 2

In the marine silicon cycle, silicon travels from the land into the oceans *via* rivers and groundwater. Near the ocean's surface, silicon is taken up by phytoplankton like diatoms and incorporated into their skeletons. When these organisms die, they sink to the bottom of the ocean. Along the way, some of the skeletons dissolve and release silicon back into the water, but others end up buried in the sediment, along with the carbon they contain.

it to the bottom of the oceans, but not by a direct path, and it takes a very long time—maybe as much as 8,000 years [3]. In coastal areas, river waters and groundwaters supply the top layers of the ocean with dissolved silicon—a tasty new food for the organisms there. This ocean layer is home to many tiny organisms called **phytoplankton** that need sunlight to survive. Every spring and summer, the light from the sun and nutrients from the rivers create perfect growth conditions for a very important type of phytoplankton, called diatoms. Billions of diatoms grow in every ocean worldwide, but there is one special place on Earth where diatoms and other silicon-using marine organisms flourish, called the Southern Ocean.

PHYTOPLANKTON

Tiny marine plant-like organisms that live in the water, like diatoms. They make their own food using sunlight and nutrients, produce oxygen and are an important part of aquatic food webs.

Diatoms use silicon to build their armor-like skeletons, much like we use calcium to build strong bones. The skeleton of diatoms is very strong compared to other phytoplankton. As diatoms grow, they eat up all the dissolved silicon, but they also remove CO_2 from the surface waters of the ocean and produce most of the oxygen we breathe. At the end of summer, diatoms die and sink toward the deeper layers of the ocean. Some diatom skeletons dissolve, and some continue their journey to the very bottom of the ocean. There, on the deep, dark seafloor, diatom skeletons get buried in marine sediments (mostly made of mud). This means the carbon they have removed from the surface waters is buried, too. This very important process of CO_2 removal from the atmosphere by sinking diatoms is called the **biological carbon pump**. Through this process, diatoms in all of the world's oceans contribute to 40% of the oceanic carbon removal [4].

BIOLOGICAL CARBON PUMP

A set of processes, including photosynthesis performed by algae, that trap or "pump" CO2 from the atmosphere into the ocean, where it is stored for a long time.

Silicon is also essential for other marine organisms such as sponges, and the **zooplankton** group called radiolarians (read more here). Just like diatoms, these organisms take part in the marine silicon cycle and help to remove CO_2 from the atmosphere.

ZOOPLANKTON

Small aquatic animals that are an important part of the food web and play a key role in the carbon and nutrient cycles of aquatic ecosystems.

HOW IS SILICON RELEVANT TO OUR LIVES?

The silicon cycle is important in our everyday lives, even though we may not realize it. Understanding the past and present marine silicon cycle helps us to better predict how the environment will respond to climate change. It is especially important to understand how diatoms, radiolarians, and sponges will react to a rapidly changing environment. Diatoms are the first step in the **marine food web**. Zooplankton eat diatoms; larger fish and whales eat the zooplankton, and so on, moving energy up the food web. This means that if diatoms disappear from the ocean, the entire food web will suffer. Whales would not be the only ones without food, fishermen would be, too. This would have a lot of consequences because more than 3 billion people rely on fisheries.

MARINE FOOD WEB

A complex system of interrelated food chains that exists in aquatic environments, from tiny plankton to large whales.

Diatoms need special, stable conditions to grow. The climate has changed in the past, and so have diatoms, but these changes were slower compared to what we are experiencing today. Unfortunately, we have already observed a replacement of diatoms by other organisms in some places, for example in the Baltic Sea. These replacements disturb the food web and impact food availability for many people (read more here).

Diatoms, sponges, and radiolarians are also helping us to create better and more efficient designs in engineering. These organisms are great engineers themselves. The processes they use to transform silicon into silicon-based skeletons are of great interest. Their skeleton structures are beautiful but also very strong. Engineers are trying to recreate the same patterns used in the skeletons of diatoms, sponges, and radiolarian (Figure 3), which could make building structures or fabrics stronger. In addition, diatoms may be the perfect candidate to help us build the next generation of solar panels because their skeleton structure contains many holes that efficiently capture sunlight.

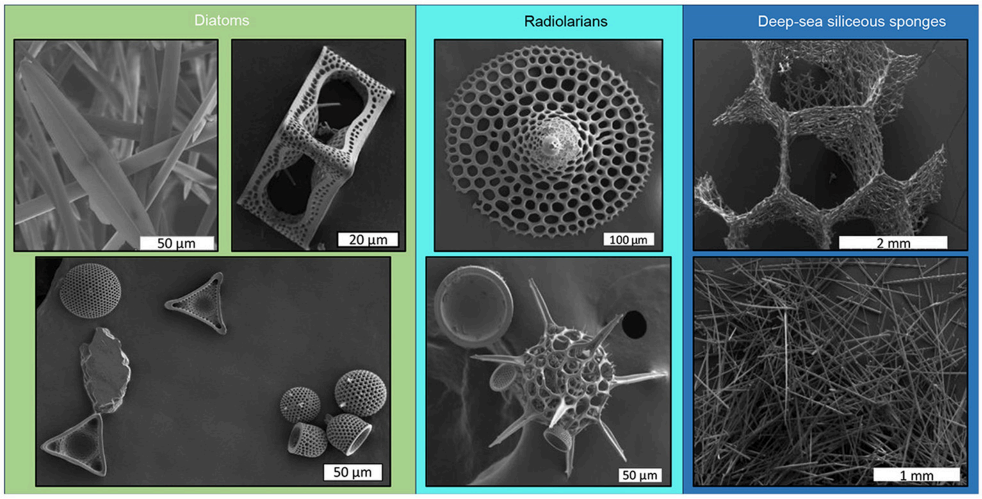


Figure 3

Figure 3

Pictures made with a powerful microscope (called a scanning electron microscope) showing examples of the silicon skeletons of diatoms, radiolarians, and deep-sea sponges. The scale bars show how tiny these skeletal structures are: 1 mm = 0.1 cm, 10 µm = 0.001 cm (Photo credits: Lucie Cassarino).

Deep sea sponges are another example of how amazing features of nature might help humans. Scientists are studying the connection between sponges and microbes (tiny organisms living within the sponges), which is giving them information on new molecules that could be used to produce human medicines. There are probably many more ways the silicon cycle can help us in our daily lives, so scientists have even more to discover.

In summary, the silicon cycle plays a key role in the health and stability of Earth's ecosystems. It helps to regulate the levels of nutrients and carbon in the atmosphere and oceans. This, in turn, affects the planet's health, which is vital for our survival and well-being. By studying the silicon cycle, scientists can gain a better understanding of Earth's natural systems and how they are impacted by human activities. This knowledge can help us to make the best possible decisions about how we use and manage our natural resources.

ACKNOWLEDGMENTS

This abstract is part of a series of six manuscripts about the marine silicon cycle put together by the ECR SILICAMICS group. We thank the SILICAMICS ECRs consortium for its enthusiasm for putting this project together. Authors thank the European Union's Horizon 2020 research and program under the Marie Skłodowska-Curie grant agreement No 899546, Bundesministerium für Bildung und Forschung for the project "SO289—S Pacific GEOTRACES" funding, which supported this work.

REFERENCES

1. Zhang, S., Bai, X., Zhao, C., Tan, Q., Luo, G., Wang, J., et al. 2021. Global CO_2 consumption by silicate rock chemical weathering: its past and future. *Earths Future* 9:e2020EF001938. doi: 10.1029/2020EF001938
2. Tao, Z., Gao, Q., and Liu, K. 2011. Carbon sequestration capacity of the chemical weathering processes within drainage basins. *Quat. Sci.* 31:408–16. doi: 10.3969/j.issn.1001-7410.2011.03.02
3. Tréguer, P., Sutton, J., Brzezinski, M., Charette, M. A., Devries, T., Dutkiewicz, S., et al. 2021. Reviews and synthesis: the biogeochemical cycle of silicon in the modern ocean. *Biogeosciences* 18:2269–89. doi: 10.5194/bg-18-1269-2021
4. Tréguer, P., Bowler, C., Moriceau, B., Dutkiewicz, S., Gehlen, M., Aumont, O., et al. 2018. Influence of diatom diversity on the ocean biological carbon pump. *Nat. Geosci.* 11:27–37. doi: 10.1038/s41561-017-0028-x

SUBMITTED: 02 March 2023; **ACCEPTED:** 26 December 2023; **PUBLISHED ONLINE:** 25 January 2024.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Rafiad Islam

CITATION: Cassarino L, Pickering RA, Zhang Z and Liguori B (2024) The Silicon Cycle in the Ocean. Front. Young Minds 11:1178327. doi: 10.3389/frym.2023.1178327

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

JASRAH, AGE: 10

Jasrah is a Grade 5 student interested in Biology, Biodiversity, Environmental pollution, and Animals. Her curiosity and desire to learn more about the natural world are evident. She respects the environment and is dedicated to exploring ways to preserve biodiversity and reduce pollution. Jasrah is eager to share her knowledge and insights with others. With her inquisitive mind and commitment to the environment, she is sure to make a positive impact in the years to come.

AUTHORS

LUCIE CASSARINO

My research interests are modern marine biogeochemical cycles with a focus on the silicon cycle. It consists of understanding how marine nutrients are distributed in the ocean, giving information on the wellbeing of organisms that need silicon to survive, such as diatoms, siliceous Rhizaria and siliceous sponges. My work combines many fields such as chemistry, geochemistry, physics, biology, and geology to get the best pictures of the cycles. I also use very fine chemical tools (stable isotopes) to understand the influence of the ocean dynamic on phytoplankton distribution, to understand how siliceous organisms build their skeleton, and to help scientists looking at the past (from sediment fossils). My research has a particular interest in the polar environments but also relies on other field data and laboratory experiments. I am at the moment creating an observatory that will be deployed in arctic waters to follow concentration of nutrients and the physical parameters in real time. *lucie.cassarino@univ-brest.fr

REBECCA A. PICKERING

My research interests are modern marine biogeochemical cycles with a focus on the silicon cycle. It consists of understanding how marine nutrients are distributed in the ocean, giving information on the wellbeing of organisms that need silicon to survive, such as diatoms, siliceous Rhizaria and siliceous sponges. My work combines many fields such as chemistry, geochemistry, physics, biology, and geology to get the best pictures of the cycles. I also use very fine chemical tools (stable isotopes) to understand the influence of the ocean dynamic on phytoplankton distribution, to understand how siliceous organisms build their skeleton, and to help scientists looking at the past (from sediment fossils). My research has a particular interest in the polar environments but also relies on other field data and laboratory experiments. I am at the moment creating an observatory that will be deployed in arctic waters to follow concentration of nutrients and the physical parameters in real time. *Rebecca.Pickering@geol.lu.se

ZHOULING ZHANG

As a marine chemist, my research focuses on (bio)geochemical cycling and ocean circulation. I am curious about the sources of ocean essential elements, such as from rivers, sediments, hot hydrothermal vents, etc. My aim is to figure out how these elements change in the ocean because of (bio)geochemical processes. I have explored lots of different parts of the ocean from estuaries to the open ocean, like the Amazon estuary, the Congo shelf, the Baltic Sea, the South China Sea, and the South Pacific Ocean.

BIANCA LIGUORI

My research focuses on the biogeochemical silicon (Si) cycle using stable Si isotopes as a tool. The stable Si isotope composition of different reservoirs like seawater, porewater or diatoms bears information on the dominant pathways and processes by which Si is transported to and cycled in the ocean. Therefore, understanding these factors is of vital importance for our general understanding of the global Si cycle. For that, I work with seawater, particulate, marine pore waters and sediment samples from the Arctic and Pacific Oceans.

BIODIVERSITY
Published: 24 January 2024
doi: 10.3389/frym.2024.1122119

WATCHING OUT FOR CORAL REEFS WITH FORAMS

Elsa B. Girard[1,2*] *and Willem Renema*[1,2]

[1] *Marine Biodiversity Research Group, Naturalis Biodiversity Center, Leiden, Netherlands*

[2] *Department of Ecosystem & Landscape Dynamics (ELD), Institute for Biodiversity and Ecosystem Dynamics – IBED, University of Amsterdam, Amsterdam, Netherlands*

YOUNG REVIEWERS:

JUDE
AGE: 15

MARGARIDA
AGE: 15

Lots of creatures live in coral reefs, including some tiny ones you might never have heard of. In this article, we will tell you about the importance of Foraminifera (also called forams), unicellular organisms with shells, that contribute to coral reefs in many ways. Just like corals, some forams living on the seafloor live closely together with microalgae. Some forams also thrive in similar environmental conditions (sunlight, temperature, salt) as corals. For this reason, forams can be used as reef "sensors", to keep track of the overall health of coral reefs. They can even help to detect poor environmental conditions that might harm coral growth in the future. In this article, we will look at a study of an Indonesian reef ecosystem in which the foram communities living on the seafloor were monitored between 1997 and 2018.

WHAT ARE LARGE BENTHIC FORAMINIFERA?

Coral reefs are the rainforests of the oceans. They harbor not only corals, but a wealth of other animals like sea urchins, sea cucumbers,

PLANKTONIC

Organism that lives in the water column.

BENTHIC

Organism that lives on the seafloor.

MICROALGAE

Microscopic algae consisting of a single cell.

sea feathers, sea stars, and turtles. Coral reefs also are home to many tiny creatures, like sea slugs, sea horses, shrimps, and a group you may not have heard of, called Foraminifera. Foraminifera (also called forams) are unicellular organisms with animal-like cells. Most forams have shells shaped like a cone, ball, star, coin, or swirl, while others have no shells. Forams are not limited to coral reefs. Some live floating in the ocean, known as **planktonic** forams. Others, known as **benthic** forams, live on the seafloor, from the deepest part of the ocean to the shoreline. Benthic forams are divided in two groups: small and large. The large benthic forams can range from 0.5 mm to 20 cm. They can grow to large sizes because they have a special relationship with **microalgae**. This relationship likely benefits both the microalgae and the forams. Microalgae use sunlight for photosynthesis to produce sugars, just like plants. The sugars provided by the microalgae give the foram energy to make its shell [1]. In exchange, the foram offers shelter and nutrients to the microalgae. However, scientists still do not fully understand this relationship and how it is affected by the surrounding environment, so they are still actively researching it.

COMMUNITY

Group of populations of two or more different species that occupy the same geographical area at the same time.

Large benthic forams and reef-building corals need similar temperatures, nutrients, and amounts of sunlight to thrive, because both rely on their relationship with microalgae. Foram communities change faster than corals because they are unicellular organisms and have a shorter life span. As environmental conditions change, some foram species will survive better than others, and changes can be seen in their **communities**. If environmental conditions are not good for coral growth, an effect can be seen in the foram community first. Early after the environment changes, corals might not yet show any signs of deteriorating health. This means that the number of species and quantity of large benthic foram species that form a community can be used to monitor the health of coral reefs [2].

CORAL TRIANGLE

The region of the Indo-Pacific grouping of the Philippines, Malaysia, Indonesia, Papua-New-Guinea, and Solomon Islands where the highest density of species present in coral reefs is found.

ABUNDANCE

Number of individuals for a given species.

A STUDY OF FORAMS IN THE SPERMONDE ARCHIPELAGO IN INDONESIA

To figure out for sure whether changes in large benthic foram communities can predict upcoming coral reef damage, researchers did a 20-year study (1997–2018) of large benthic foram communities in the Spermonde Archipelago, Sulawesi, Indonesia, located in the middle of the **Coral Triangle** [3]. They sampled the foram communities at 12 islands across the Spermonde Archipelago five times during the course of the study. A total of 26 large benthic foram species were identified by examining their shells with a microscope (Figure 1). Next, the forams were counted, to know how many shells of each species were in each sample (called the **abundance**). Samples were taken in two different reef habitats: the reef flat (very shallow, 1–2 m deep) and the reef slope (ranging from 1 to 30 m deep) (Figure 2). The researchers found that the foram community composition was

DIVERSITY

Quality of including different organisms in a group.

Figure 1

Eighteen of the most common foram species found on the reef slope and the reef flat habitats in Indonesia. The sizes of the forams vary between 0.5 and 5 mm in diameter, with *Neorotalia* being the smallest and *Parasorites*, *Marginopora vertebralis* and *Amphisorus* being the biggest. Images were not all taken at the same scale.

very different between the reef flat and the reef slope. The **diversity** of foram species was higher (meaning there were more species) on the reef slope than on the reef flat. The diversity also depended on how far the island was from the mainland.

Figure 1

This study also showed that the composition of the large benthic foram communities changed from one year to another over the 20-year study period (Figure 2). Corals were more abundant in 1997, especially on the reef flat. At that time, the seafloor was dominated by some lentil-shaped forams (*Amphistegina*). The algal component on the seafloor increased greatly between 1997 and 2018, so did some star-shaped forams (*Neorotalia* and *Calcarina)*. Those

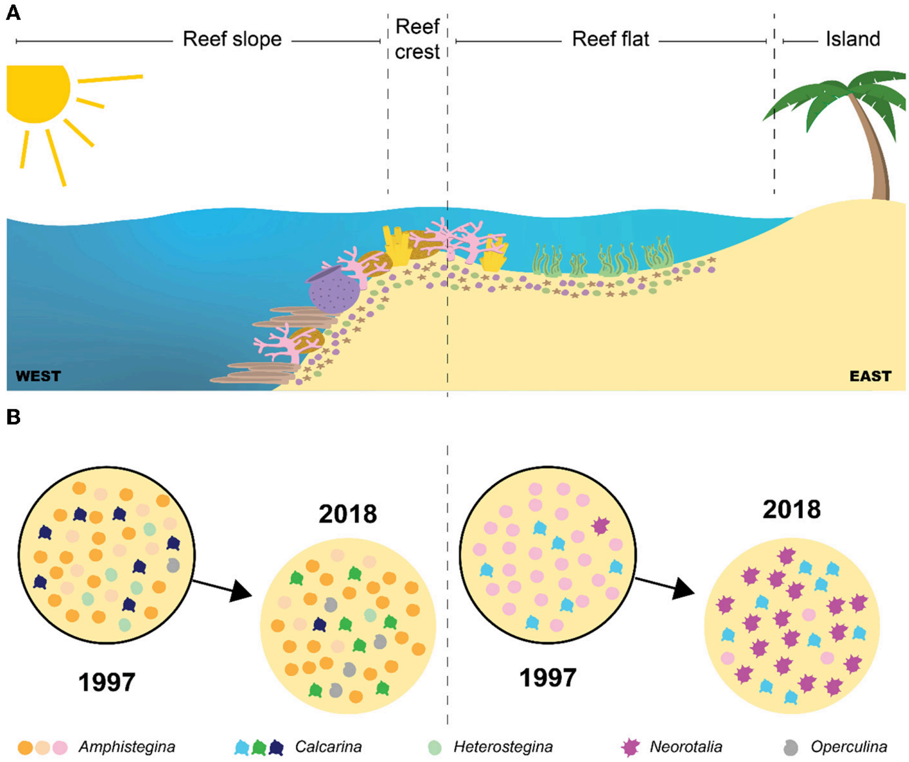


Figure 2

(A) A reef is divided in three zones: the reef flat, the reef crest and the reef slope (divided by dashed lines). A reef community consists of many organisms, including corals, sponges, fish, and forams. **(B)** Between 1997–2018, changes were seen in the composition of the foram community, especially on the reef flat where the number of star-shaped foram increased exponentially. Every foram species has its own shape and color. Figure adapted from Girard et al. [3].

star-shaped forams like to live in environments where algae also grow. Usually, when the environment is suited for algal growth, it is not for coral growth. The shift in the foram community over time therefore indicated a deterioration of the coral reef system in the Spermonde Archipelago.

The research showed us that many things can shape the composition of the foram communities: the type of material they grow on (called the **substrate**), island population, and distance from mainland, to name only a few [3, 4].

SUBSTRATE

A natural or artificial material that organisms can settle, grow, and live on or in.

MORE ALGAE GROWING IN THE SPERMONDE ARCHIPELAGO

Large benthic forams live on multiple substrates. Some thrive on the sand or algae. Others prefer coral rubble, made of dead pieces of coral skeleton. On coral rubble, there are lots of little cracks and holes to take refuge and settle in. Over the course of the 20-year study, the substrate in the Spermonde Archipelago changed (Figure 3). It started off in 1997 with more than 60% coral rubble, clean of algae. From 2012 on, more than 80% of the substrate became covered by small algae [3]. Despite the change in the substrate type over time, the amount of surface covered by living corals did not drastically decrease and even seems to have slightly increased in recent years [5].

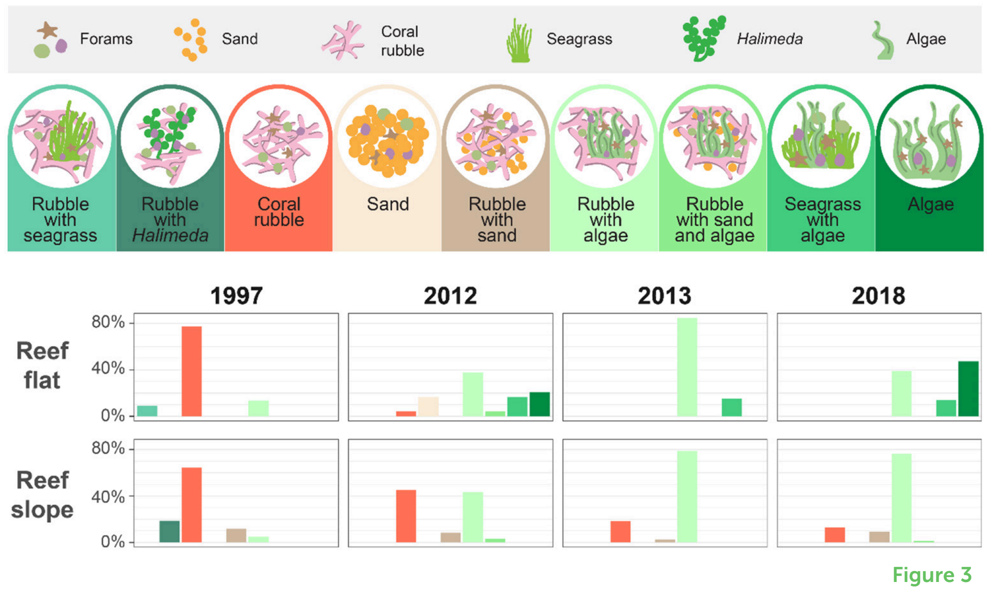


Figure 3

Changes in the substrate type on coral reefs between 1997 and 2018. The y axis shows the abundance of each type of substrate in the samples taken during the study. On the x axis, you can see the years when the samples were collected. With time, there is a decrease in the abundance of clean coral rubble (orange) and an increase in the abundance substrates with algae (various shades of green). This gives us the indication that the environment in the reef is more suited to algal growth, which might impact coral growth negatively. Figure adapted from Girard et al. [3].

Communities of algae are primarily shaped by how much they grow and how much they are eaten by herbivores (animals that feed on algae and plants). Algae grow faster when there are a lot of nutrients in the water, especially phosphorus and nitrogen. Algae also thrive when they get a lot of sunlight, like they do in shallow water [6]. The more people live on an island, the more pollution enters the water. Because pollution often contains phosphorus and nitrogen, the more pollution is in the water, the faster algae will grow—especially in the sunny, shallow parts of the reef. Pollution also decreases the number of fish eating the algae. Thus, the combination of faster growth and less algae being eaten results in more algae in the reef habitat. This sequence of events most likely changed the benthic habitats on the reef flat, which then affected the composition of large benthic foram communities. Indeed, many foram species seem to prefer a type of substrate [3].

Some foram species seemed to have strong preferences about which island they grew on, island's population, and where the island is located. The distribution of these forams is probably related to the water quality and amount of man-made pollution present in various areas of the Spermonde Archipelago. Scientists still do not fully understand the effects of substrate type and water quality on forams [3, 4].

FORAM MONITORING COULD HELP CORAL REEFS

Based on the study we just described, and previous studies from different regions of the world, we know that large benthic forams are very sensitive to both water quality and substrate type. Their community shifts can tell us about changes in environmental conditions that sensitive coral reefs are exposed to. Monitoring large benthic forams on a regular basis may help scientists to detect early stages of coral reef deterioration, as seen in the Coral Triangle and the Great Barrier Reef.

Coral reefs are hotspots of ocean biodiversity. Many human populations rely on reefs for food and tourist activities. When they are well managed, reefs can be sustainably used and preserved. Thus, it is very important to monitor the health of coral reefs. Closely monitoring communities of large benthic forams gives us a good estimate of coral reef health. Additionally, monitoring foram communities may also be used as a warning signal for early coral reef deterioration—hopefully in time to take action against whatever is damaging the reefs.

ACKNOWLEDGMENTS

We would like to thank the young reviewers for their precious comments. This work was funded by the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement (4D-REEF, No 813360).

REFERENCES

1. Prazeres, M., Renema, W. 2019. Evolutionary significance of the microbial assemblages of large benthic Foraminifera. *Biol. Rev. Camb. Philos. Soc*. 94, 828–848. doi: 10.1111/brv.12482
2. Hallock, P., Lidz, B. H., Cockey-Burkhard, E. M., Donnelly, K. B. 2003. Foraminifera as bioindicators in coral reef assessment and monitoring: the FoRAM Index. *Environ. Monit. Assess.* 81, 221–238. doi: 10.1007/978-94-017-0299-7_20
3. Girard, E. B., Estradivari, Ferse, S., Ambo-Rappe, R., Jompa, J., Renema, W. 2022. Dynamics of large benthic foraminiferal assemblages: a tool to foreshadow reef degradation? *Sci. Total Environ*. 811, 151396. doi: 10.1016/j.scitotenv.2021.151396
4. Renema, W. 2018. Terrestrial influence as a key driver of spatial variability in large benthic foraminiferal assemblage composition in the Central Indo-Pacific. *Earth-Sci. Rev*. 177, 514–544. doi: 10.1016/j.earscirev.2017.12.013
5. Teichberg, M., Wild, C., Bednarz, V. N., Kegler, H. F., Lukman, M., Gärdes, A. A., et al. 2018. Spatio-temporal patterns in coral reef communities of the spermonde archipelago, 2012–2014, I: comprehensive reef monitoring of water and benthic indicators reflect changes in reef health. *Front. Marine Sci*. 5, 33. doi: 10.3389/fmars.2018.00033
6. Han, Y., Aziz, T.N., Del Giudice, D., Hall, N. S., Obenour, D. R. 2021. Exploring nutrient and light limitation of algal production in a shallow turbid reservoir. *Environ. Pollut.* 269, 116210. doi: 10.1016/j.envpol.2020.116210

SUBMITTED: 12 December 2022; **ACCEPTED:** 08 January 2024;
PUBLISHED ONLINE: 24 January 2024.

EDITOR: Emily King, Xiamen University, China

SCIENCE MENTORS: Catherine A. Walsh and Rita Araujo

CITATION: Girard EB and Renema W (2024) Watching Out for Coral Reefs With Forams. Front. Young Minds 12:1122119. doi: 10.3389/frym.2024.1122119

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

JUDE, AGE: 15

I am a big fan of both dogs and cats. I have trained my cat to walk on a lead so we can go for walks together in my spare time. I also love music and spend a lot of time playing my guitar. I enjoy reading about biochemistry (especially plant related) and one day would like to study the subject at university.

MARGARIDA, AGE: 15

My name is Margarida. I am 15 years old and I like reading, climbing, and writing. I love science, especially astrophysics and I have absolutely no idea what I want to do when I grow up. I also really like biology.

AUTHORS

ELSA B. GIRARD

Elsa is a Ph.D. student based at Naturalis Biodiversity Center and part of the 4D-REEF European research consortium studying the past, present, and future of turbid coral reef ecosystems. Her research focuses on the changes of forams community through space and time from the Spermonde Archipelago (Indonesia). She is also improving the identification of forams using DNA without the need of sorting the species from the sediment samples under a microscope. Her research contributes to the understanding of factors driving community changes in turbid reef systems.
*elsa.girard@naturalis.nl

WILLEM RENEMA

Willem is a professor and researcher at University of Amsterdam and Naturalis Biodiversity Center as well as project leader of the 4D-REEF European research consortium. His research focuses on the evolution and ecology of large benthic forams, by studying the role of those forams in their environments. They are an important organisms participating to the production of sand in the reef, and were even more so in the past. He relies on a thorough understanding of their shell shape and genetic evolution, from both fossil and living forms.

EARTH SCIENCES
Published: 22 January 2024
doi: 10.3389/frym.2023.1076771

OUR BLUE PLANET: CONNECTING HUMANS AND THE OCEAN

Michael Kriegl[1,2*], Sophia Kochalski[3], Tanja M. Straka[4], Philipp Gorris[5,6], Achim Schlüter[1,7] and Lotta C. Kluger[2,8]

[1] *Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany*
[2] *Center for Ocean and Society, Kiel University, Kiel, Germany*
[3] *CRETUS, Department of Applied Economics, University of Santiago de Compostela, Santiago de Compostela, Spain*
[4] *Institute of Ecology, Technische Universität Berlin, Berlin, Germany*
[5] *Institute of Environmental Systems Research (IUSF) and Institute for Geography (IfG), University of Osnabrueck, Osnabrück, Germany*
[6] *Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden*
[7] *Constructor University, Bremen, Germany*
[8] *Department of Agricultural Economics, Kiel University, Kiel, Germany*

YOUNG REVIEWERS:


ELLIANA
AGE: 10


JULIET
AGE: 12


WILLIAM
AGE: 11

Dive into the incredible world of the ocean, a place full of wonder and beauty! The ocean is like a superhero, providing us with tasty seafood and other vital "services". But trouble looms: climate change, plastic pollution, and intensive fishing endanger the ocean's superpowers. Your help is needed to save the day! To keep the ocean healthy, we must understand how it works. Get ready to explore its mysteries through gigantic "webs" of interactions that reveal how we are connected to the ocean, how our actions impact the environment, and how the environment affects us. These webs are called social-ecological networks, and they are like maps that help us

YALE PATHWAYS TO SCIENCE PROGRAM

AGES: 11–13

solve the ocean's problems. Together, we can use social-ecological networks to secure a sustainable future for our blue planet. So, put on your diving mask, grab your snorkel, and let us make a splash for the ocean!

THE INTERCONNECTED WORLD OF THE OCEAN

The ocean is a place full of wonder. From colorful coral reefs to majestic whales to the tiniest creatures floating through the water, it is teeming with life. But there is more to the ocean than just its beauty. In fact, for us humans, the ocean is like a superhero by our side, providing us with essential "services" that we depend on for our very existence. For example, the ocean regulates the climate by absorbing carbon dioxide, and it produces oxygen for us to breathe. And think of all the delicious fish and seafood that we can enjoy thanks to the ocean!

But here is the challenge: the ocean is facing some serious issues, and humans are often responsible for them. Climate change is causing the water to warm up and sea levels to rise. When people catch too many fish, the balance of the ocean ecosystems can get messed up. In addition, millions of pieces of plastic trash find their way into the ocean every single day. If we are not careful, our ocean hero could lose its superpowers!

So our mission is crystal clear: We must keep the ocean healthy and strong.

To do that, we first need to understand the ocean and its mysteries. Imagine putting on your diving mask and exploring the underwater world. Hold your breath as you observe crabs, octopus, and fish in their natural habitat. Watch as these animals move across the seafloor, hunt for a tasty lunch, and interact with each other. These interactions in the natural world make up the **ecological** side of the ocean's story [1].

ECOLOGICAL

Everything about how animals and plants interact with each other and their environment.

But humans are part of the ocean, too. Think about fishers casting their nets along the coast and exchanging ideas about the best fishing spots, or families enjoying beach holidays and collecting seashells. The ocean offers so many opportunities, but here is the thing: everything we do can have an impact on the ocean. This is the **social** side of the ocean's story, where we can see how our actions, choices, and interactions matter to the ocean's health [2].

SOCIAL

Everything about how people live, communicate, and work together in groups and communities.

Solving problems in the ocean is hard. That is why scientists usually try to break these problems into smaller pieces, to better understand each part on its own. But sometimes this can be like trying to solve a puzzle with missing pieces! Imagine tackling the issue of overfishing by only looking at the biology and behavior of a specific type of fish, but ignoring their important role in the food web, or the actions of fishers.

So, here is the big secret: We cannot just focus on one side of the ocean's story and ignore the others. We must discover how everything in and around the ocean is connected, from tiny creatures on the seafloor to the people who live along the coast. This way of thinking is called **systems thinking** and it helps us better understand the web of relationships that shape the ocean. Through a combined understanding of all related aspects, we can find the best solutions to keep the ocean healthy.

SYSTEMS THINKING

A way of understanding how things fit together to form a bigger picture (and not just looking at the individual parts).

WHAT ARE SOCIAL-ECOLOGICAL NETWORKS?

How do scientists think about and study the different parts of the ocean's story and their connections? They use something called **social-ecological networks** [3]. Picture a gigantic web connecting all the parts of the ocean system that we just discussed (Figure 1). In the language of networks, the different components of the ocean system, such as marine animals and people, are called **nodes**. The arrows or **links** connecting the nodes show their interactions. One part of a social-ecological network shows the relationships between people (the social network), like fishers sharing knowledge about fishing spots. The other part shows how ocean inhabitants, such as fish or crabs, interact with each other and the environment (the ecological network). This is like a big puzzle of who eats whom. The network also includes the connections that cross these two worlds, for example when people catch fish or pollute the ocean with plastic trash.

SOCIAL-ECOLOGICAL NETWORK

A network of the connections between people as well as animals, plants, or ecosystems.

NODE

A thing in a network, like a person or fish, that is connected to other things.

LINK

A connection between two things in a network, such as people talking to each other or one fish eating another one.

In essence, a social-ecological network is like a map that reveals how everything in and around the ocean is connected. It helps us understand how our actions affect the ocean and how the ocean affects us.

WHAT HAPPENS WHEN WE IGNORE SOCIAL-ECOLOGICAL CONNECTIONS?

Let us look at two examples to see what happens when we ignore these connections.

First, Canada used to have one of the largest cod fisheries in the world, providing a livelihood for many fishing communities. But because people caught too many fish without thinking about what might happen, the cod disappeared. This had a big impact on the animals that relied on cod as their food and set off a chain reaction in the local food web. The ecosystem was permanently changed and the effects for local fishers were devastating. Thousands of people lost their jobs, and

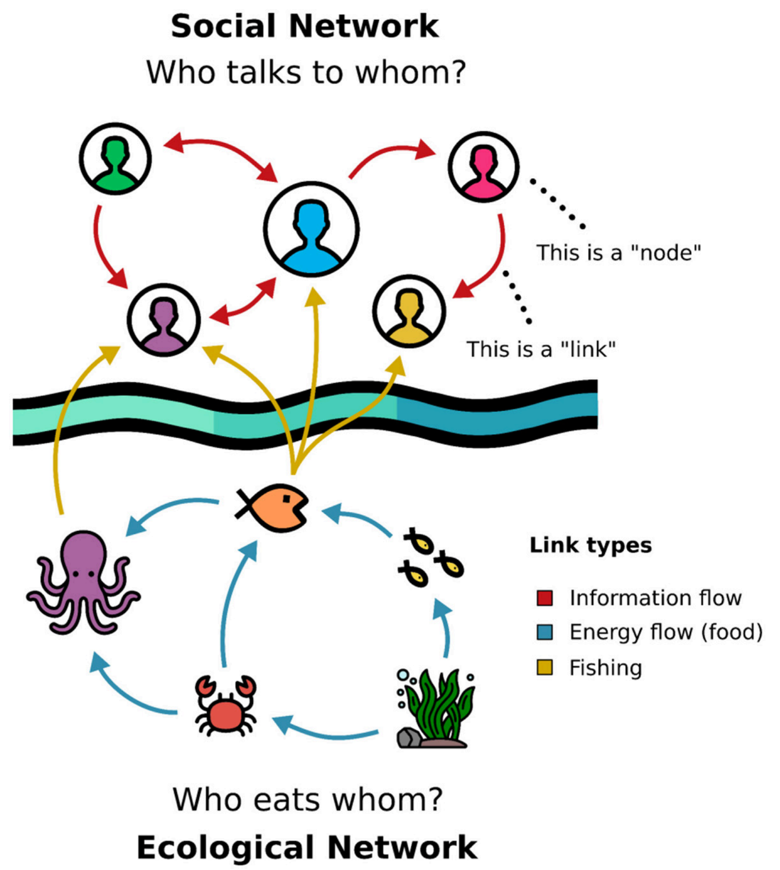


Figure 1

A social-ecological network shows the connections between people and nature. Each component is a node and the interactions between them are called links. The top half shows a social network, with red arrows illustrating the flow of information between people. The bottom half shows an ecological network, illustrating the relationships between ocean inhabitants. The blue arrows highlight the flow of energy, for example when one species eats another. Activities like fishing create a bridge between the ecological and social sides of the network, as shown by the yellow arrows. All of the connections together form a complete social-ecological network.

MARINE PROTECTED AREA

A place in the ocean where special rules, like "No Fishing!", help to protect the underwater world.

the local communities suffered greatly. Despite considerable efforts, the fishery has not recovered to date.

As another example, **marine protected areas** are special zones in the ocean designed to preserve marine life. They can be safe havens for fish and other animals when there is excessive fishing. But if we create marine protected areas without considering the people that depend on fishing for a living, this can cause problems. To make ends meet, fishers might turn to destructive fishing techniques or continue to fish illegally, harming marine life. This worst-case scenario has already occurred in several places around the world.

Both examples show why it is important to consider the links between people and nature: could the fishery collapse in Canada have been prevented if we had considered the ecological side of the story? Or can involving local fishers in decision-making prevent negative outcomes of marine protected areas? To make better decisions that will lead us toward a sustainable future, we must understand social-ecological connections.

Of course, it is not just fishing that affects the ocean. Other activities like tourism, shipping, and trash disposal also impact the ocean and the people who depend on it. All of these factors make the social-ecological network of the ocean very large and complex. To understand it, people who know a lot about the ecological side of the ocean and people who know a lot about its social side need to work together.

MANAGING OUR OCEAN USING NETWORKS

As we dive into the world of social-ecological networks, we begin to see hidden patterns and relationships. Like a game of "What if...?", we can ask questions such as: "What if we eat too much of a certain kind of fish or seafood?". They might disappear from the network, affecting people and animals that rely on them for food, such as seals, which in turn are important for tourism. Or, "What if the ocean becomes too warm for mussels, due to climate change?". They could vanish, the people who collect and sell mussels could lose their jobs and the role of mussels as cleaners of the ocean ecosystem could be disrupted. See how changes in one part of the network can have a domino effect on other parts of the system (Figure 2)?

Social-ecological networks can not only shrink, but also grow. Imagine more and more tourists discovering a new vacation spot. As they arrive and hotels open, the social part of the network grows bigger. But how many tourists can fit in the network without having a negative impact on other parts? And what happens when there are simply too many people in one place, or if they all throw their trash in the ocean?

Sometimes even small changes in one part of the network can have big effects on the whole system [4]. That is why it is important to keep an eye on the network and its essential components to make sure that our interactions with the ocean are sustainable.

When everything is in balance, life in and around the ocean is like paradise! People can enjoy delicious seafood, explore beautiful coastal places, and swim in clean waters. But when things get out of balance, it is a cause for concern. In those situations, we must come together to find solutions. Each of us can play a role in reducing pollution, supporting sustainable fishing, and respecting the people who rely on and work closely with the ocean.

Protecting the ocean is a big job, but we can team up with scientists, fishers, conservationists, community members and politicians to collaborate, share ideas and knowledge, and find solutions that keep the ocean healthy. Everyone has a role to play. Together we can use social-ecological networks to better understand the ocean and ensure a bright future for both people and nature.

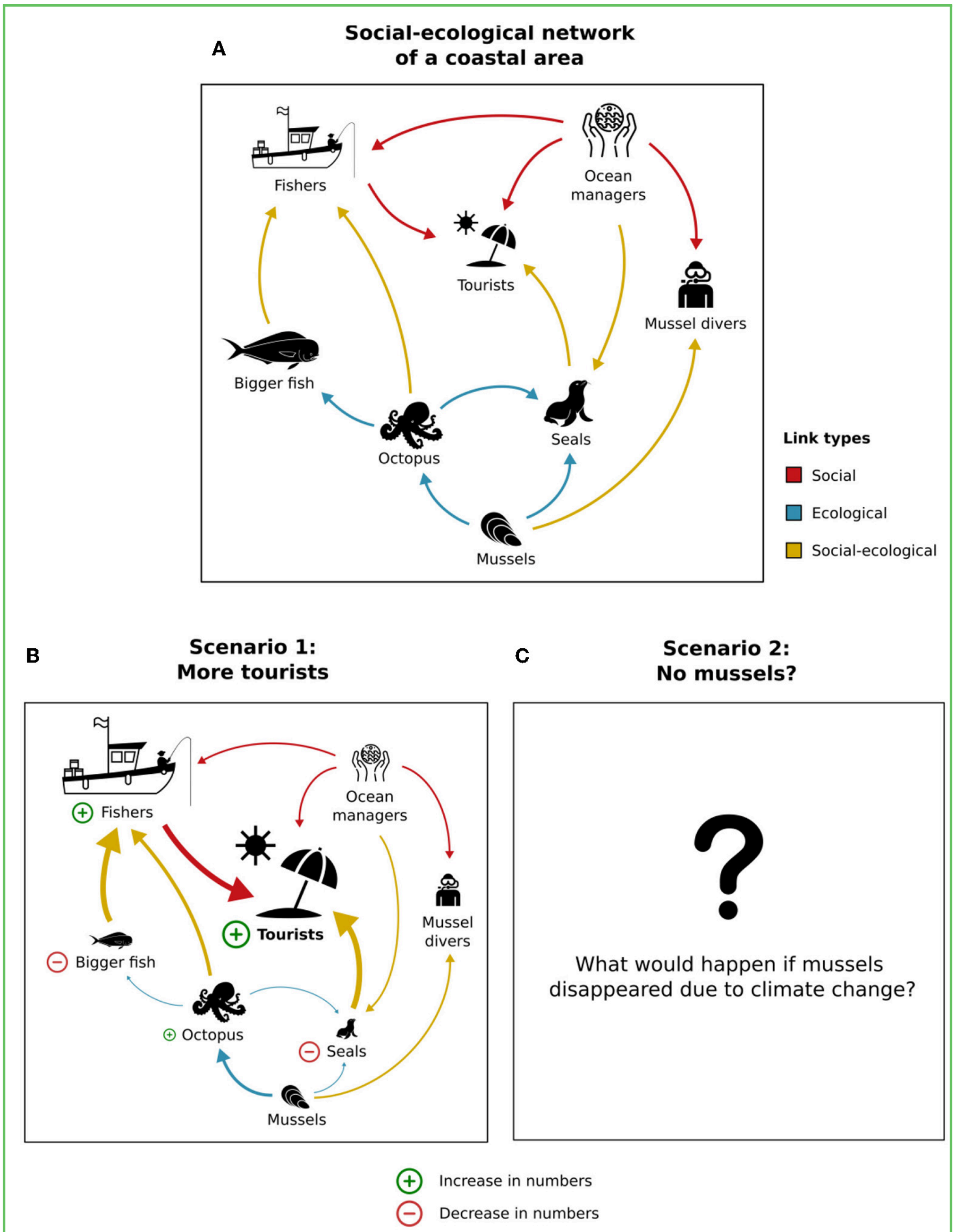


Figure 2

Figure 2

(A) A social-ecological network of a coastal area that shows the connections between people and animals living in the ocean. **(B)** What happens if more tourists (+) arrive along the coast? Seals are stressed and move away (–). A higher demand for seafood leads to more fishers (+), but fewer bigger fish (–). The numbers of octopus rise slightly (as there are less seals and bigger fish to eat them), making them the main predator of mussels. **(C)** Can you imagine what would happen if mussels slowly disappeared from the network due to climate change?

CONNECTING THE DOTS

On our blue planet, everything is connected: from the smallest ocean creatures to the food we eat in a restaurant, and from the choices we make in the supermarket to the activities of fishers along the coast. Understanding all these links empowers us to be more mindful and caring toward nature. Together, we can make a positive impact on the ocean. Using social-ecological networks, we can uncover the web of relationships between people and nature. These networks provide us with a big-picture perspective and help us to make smart decisions to keep the ocean in balance. So, let us use this powerful tool to protect the ocean and all the living things that call it home!

REFERENCES

1. Östman, Ö., Eklöf, J., Eriksson, B. K., Olsson, J., Moksnes, P. O., and Bergström, U. 2016. Top-down control as important as nutrient enrichment for eutrophication effects in North Atlantic coastal ecosystems. *J. Appl. Ecol.* 53:1138–7. doi: 10.1111/1365-2664.12654
2. Kriegl, M., Kluger, L. C., Holzkämper, E., Nagel, B., Kochalski, S., and Gorris, P. 2021. How important are social networks in times of environmental crises? *Easy Soc. Sci.* 66:11–20. doi: 10.15464/easy.2021.002
3. Kluger, L. C., Gorris, P., Kochalski, S., Mueller, M. S., and Romagnoni, G. 2020. Studying human–nature relationships through a network lens: a systematic review. *People Nat.* 2:1100–16. doi: 10.1002/pan3.10136
4. Newman, M. E. J. (2018). *Networks*. *2nd Edn*. Oxford: Oxford University Press.

SUBMITTED: 21 October 2022; **ACCEPTED:** 26 December 2023;
PUBLISHED ONLINE: 22 January 2024.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Mitchell Rogers and Rob Condon

CITATION: Kriegl M, Kochalski S, Straka TM, Gorris P, Schlüter A and Kluger LC (2024) Our Blue Planet: Connecting Humans and the Ocean. Front. Young Minds 11:1076771. doi: 10.3389/frym.2023.1076771

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

ELLIANA, AGE: 10
I am in 5th grade and 10 years old. I like swimming, gymnastics, and hiking. I also like to do arts and crafts.

JULIET, AGE: 12
I am 12 and in the seventh grade. I enjoy going to the beach and playing golf on the weekend.

WILLIAM, AGE: 11
I am 11 years old and in the 6th grade. I love swimming, singing, dancing, and gaming.

YALE PATHWAYS TO SCIENCE PROGRAM, AGES: 11–13
We are seven middle school students from New Haven, CT who love learning about science! We are excited about protecting the environment and want to do more for preserving our future. Most of us have pets we like to play with, such as dogs, cats, birds, and even reptiles. For fun, some of us enjoy playing sports, making crafts, or cooking new things.

AUTHORS

MICHAEL KRIEGL
Michael Kriegl is a marine social-ecologist and network scientist fascinated by the connections between people and the ocean. He wants to understand how social and ecological systems work together and what this means for the management of ocean resources. In addition, Michael is passionate about communicating science and sparking curiosity in young minds. He has worked along the Pacific coast, the Baltic Sea, Red Sea, Mediterranean, and the Arctic Ocean. *michael.kriegl@outlook.com

SOPHIA KOCHALSKI
Sophia Kochalski is an interdisciplinary fisheries scientist and she combines various methods to understand social processes in fisheries. She has worked with small-scale fisheries in Peru as well as in various European countries.

TANJA M. STRAKA
Tanja Straka is an urban ecologist with a passion for wildlife, conservation, and the natural world around us. In her work, she combines ecological research with social science theories. Tanja strongly believes that conservation is much more effective if we also understand people, as most threats to nature and wildlife are caused by human behavior.

PHILIPP GORRIS
Philipp Gorris is a social environmental scientist working on sustainable development and environmental governance. He studies how integrative approaches can be designed to effectively address environmental problems through socially just policies.

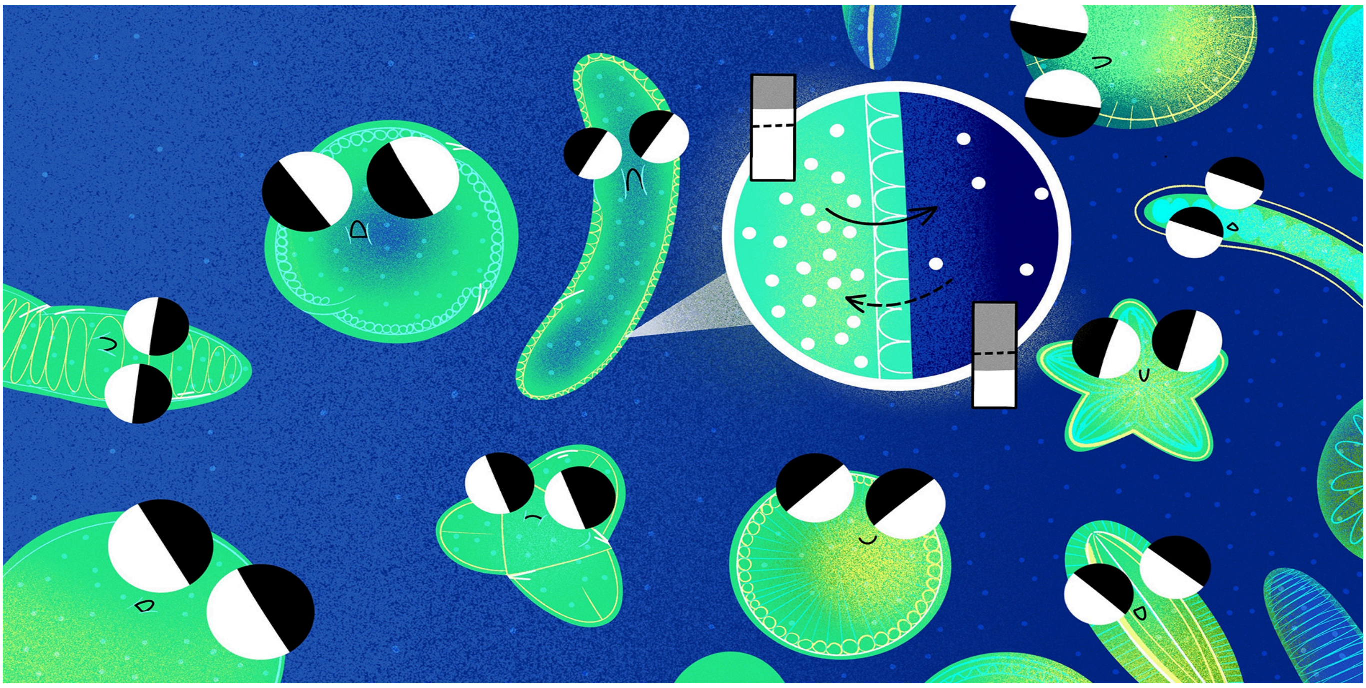
ACHIM SCHLÜTER

Achim Schlüter is a professor of social systems and ecological economics. He is interested in processes of institutional development and change, privatization, and what influences human behavior. In his work, he focuses on coastal regions in Indonesia, Peru, and Senegal as well as other countries.

LOTTA C. KLUGER

Lotta C. Kluger is an interdisciplinary researcher working on social-ecological dynamics and the sustainability of marine resource use, with a focus on aquaculture and fisheries. She has lots of experience working in coastal regions in Peru, Brazil, and other countries.

BIODIVERSITY
Published: 18 January 2024
doi: 10.3389/frym.2023.1175170



SALTY, BRACKISH, OR FRESH—SALTINESS MATTERS FOR AQUATIC SPECIES!

Leena Virta [1*], ***Alf Norkko*** [1,2] ***and Anna Villnäs*** [1,2]

[1] Tvärminne Zoological Station, University of Helsinki, Hanko, Finland

[2] Baltic Sea Centre, Stockholm University, Stockholm, Sweden

YOUNG REVIEWERS:

ETHAN
AGE: 11

LORENZO
AGE: 12

PAOLO
AGE: 9

Did you ever eat too much salty popcorn? What happened afterwards? You probably became really thirsty. There was so much salt in the popcorn that the saltiness in your body got out of balance. The same way your popcorn can be too salty or just right, the saltiness in our oceans and coastal seas can be right or wrong for the marine life. You can tell the difference between salty ocean water and fresh lake water from their different tastes and smells, and from the fact that you can float easier in the ocean. However, the effects of saltiness are much more important for animals, plants, algae, and other organisms that live in the water—for them, saltiness is a matter of life and death.

WHY DOES SALTINESS VARY IN OCEANS AND SEAS?

If you have ever gotten a mouthful of ocean water, you know that it is really salty! But did you know that saltiness is almost the same in all of the world's open oceans: approximately 35 g/L? This means that in one L of water, there are 35 g (6 teaspoons) of salt. However, there are places where saltiness can be much lower, such as in ocean water close to the coasts, and in smaller seas. That is because rivers and groundwater channels bring fresh water to these parts of the ocean. The fresh water then mixes with salty ocean water and forms what is called **brackish water**. Interestingly, the saltiness in your body is about the same as the saltiness of brackish water. Hence, your eyes will not burn if you swim in brackish water, like they would in salty ocean water or in fresh water, where the saltiness is different from that in your eyes.

BRACKISH WATER

A mixture of salty ocean water and fresh water.

SALTINESS: A MATTER OF LIFE AND DEATH

Some people like their meals saltier than other people do. Similarly, some underwater animals and plants like saltier water than others. However, for you, saltiness is a matter of taste; but for underwater organisms, it is a matter of life and death. Organisms that live in salty water have a lot of salt in their bodies. If they move to fresh water, too much water flows into their bodies to balance out the salt, causing them to swell up and die. In contrast, organisms that live in fresh water have only a little salt in their bodies. If they move to salty water, water comes out of their bodies to try to create balance, causing them to get too dry and die (Figure 1).

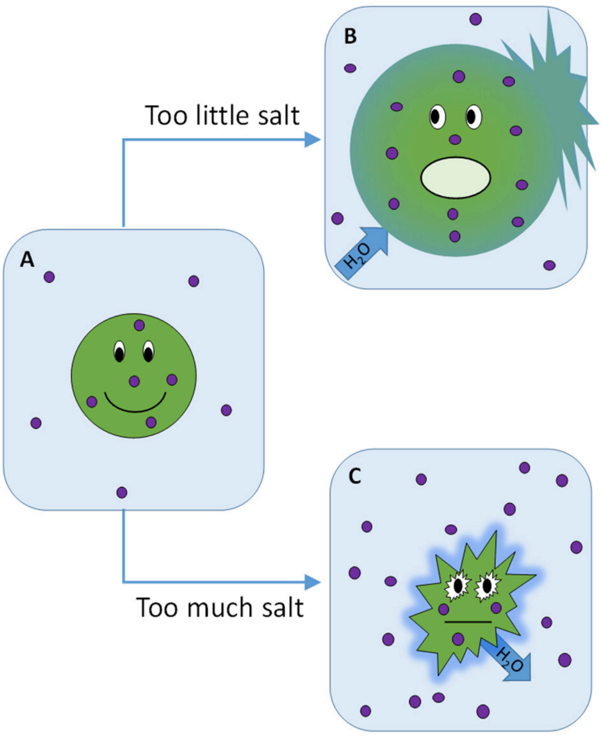


Figure 1

Figure 1

Saltiness is a matter of life and death for organisms that live underwater. **(A)** When the saltiness of the organism's body is the same as the saltiness of the water (H_2O), the organism thrives. **(B)** When the organism goes into water with saltiness that is lower than the saltiness inside its body, too much water moves into the organism to try to achieve balance, and the organism swells up and may explode. **(C)** If the organism moves into water with saltiness that is higher than the saltiness inside its body, too much water moves out of the organism, and it shrivels up and may eventually die.

BENTHIC

Living on the bottom of the ocean.

DIATOMS

One-celled, microscopic algae that have silica in their shells. They can live alone or build colonies with many individuals attached to each other.

ZOOBENTHOS

Animals living in and on the seafloor.

DIFFERENT NUMBERS OF SPECIES IN DIFFERENT KINDS OF WATER

Our research group lives and works on the coast of the Baltic Sea, which is a small coastal sea in Northern Europe. The Baltic Sea is special in terms of saltiness because it varies from salty oceanic water (>24 g/L) in the southwest, to brackish water (5–18 g/L) in the middle, to less salty and even fresh water (0–4 g/L) in the north and east (Figure 2). That is why we wanted to study how saltiness affects various species. We focused on algae (called **benthic diatoms**) and animals (called **zoobenthos**) living on the seafloor. Diatoms are tiny one-celled algae that live everywhere where there is water. They are important

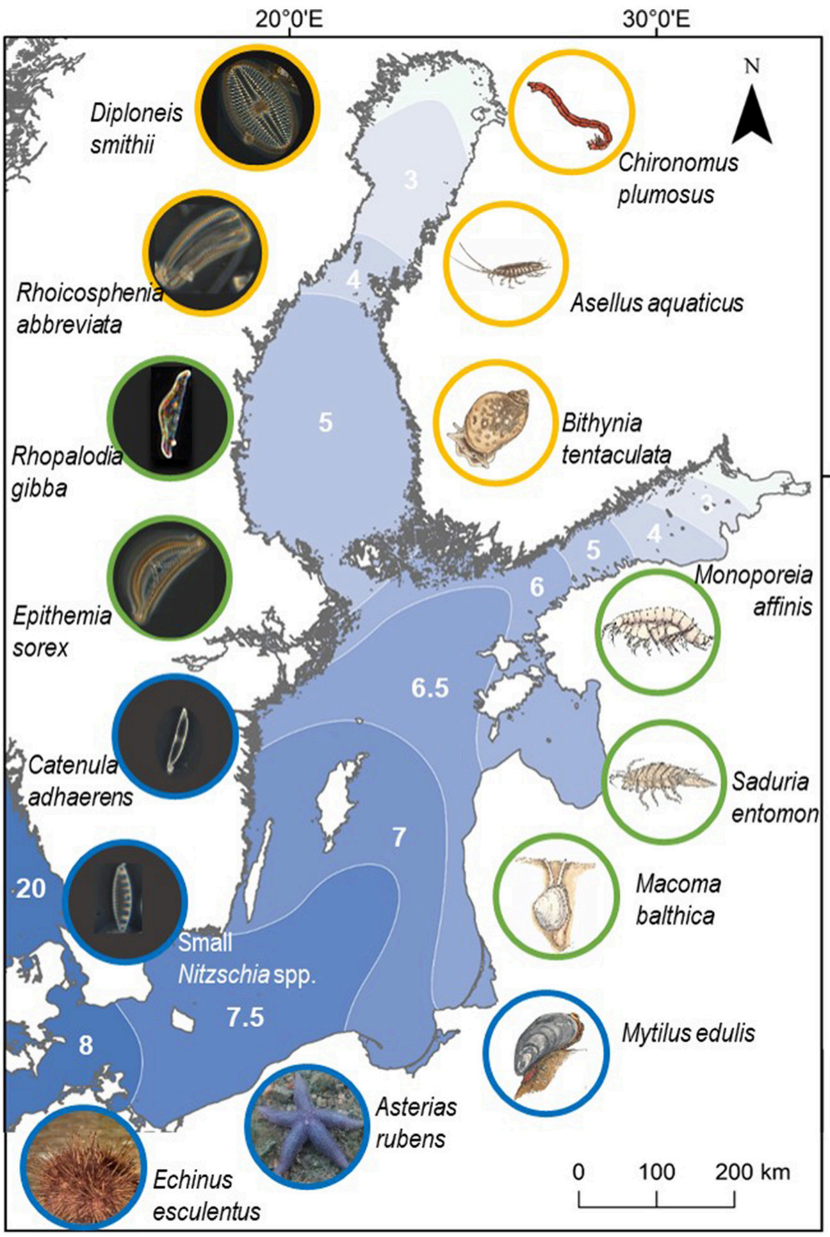


Figure 2

Figure 2

Different species of diatoms **(left side)** and zoobenthos **(right side)** live in different areas of the Baltic Sea, and one of the most important reasons for this is the variation in saltiness. Species that like fresh water (yellow circle), species that tolerate brackish water better than others (green circle), and species that prefer it salty (blue circle) are shown. Numbers show the saltiness level of each area in mg/L (Drawings by Juha and Karri Flinkman, photo of *Asterias rubens* by Camilla Gustafsson, other photos by authors).

because they make oxygen for us to breathe and they are food for small animals, such as zoobenthos. Zoobenthos live either buried in the **sediment** or they roam around on the seafloor. They are important for keeping the sediment healthy and they are also food for other animals. Zoobenthos include sea stars, sea urchins, crustaceans, bristle worms, oysters, clams, and cockles.

SEDIMENT

Sand, clay and other insoluble particles that have collected on the seafloor. Most parts of the world's seafloor are covered in sediment.

We collected samples from the seafloor in various parts of the Baltic Sea and used a microscope to identify species of diatoms and zoobenthos. We noticed that the number of species was different between areas with different saltiness [1]. The number of species of diatoms and zoobenthos was high in southern areas with high saltiness. For example, we counted up to 109 species of diatoms in one sample. The number of species was also high in the northern fresh water area but, toward the brackish water area in the middle, the number of species decreased [2, 3]. This is because only few species tolerate brackish water, which contains too much salt for species that are used to living in fresh water and too little salt for species that are used to living in the salty ocean. Another reason for the low number of species in brackish water is that brackish water areas are small, rare, and far apart, so only a few organisms have adapted to living there [4].

The number of species present, whether they are diatoms, animals, or other organisms, is important for the entire ecosystem. Ecosystems with many species often function better because each species has its own important "job" in the ecosystem, keeping it healthy. Often, ecosystems with many species can cope better with environmental changes, because even if one or two species do not survive, there are still many others left. Thus, species-poor brackish water ecosystems need to be protected, because they are home to unique plant and animal **communities** and can be vulnerable to environmental change.

COMMUNITY

Group of species that are found together.

SALTY, FRESH, OR BRACKISH?

Changes in the number of species between salty, brackish, and fresh water were not the only differences that we found in the communities of diatoms and zoobenthos. We also found completely different types of species and different sized species between salty areas and fresh water areas. Communities in brackish water were mixtures of both.

The diatom communities of the salty areas consisted mainly of species that are small and lie low to avoid being eaten. Toward the brackish and fresh water areas, we found more large and prominent species.

The zoobenthos species behaved in the opposite way. Salty areas had many big marine species, such as the sea urchin and sea stars.

These species cannot live in brackish water. The species that we found thriving in brackish water were quite few, but important, because they are food for many fish species. Common species in the brackish area were the Baltic clam and the blue mussel. We also found **glacial relicts**, which are species that were already around during the last ice age, approximately 12,000 years ago [1]. In fresh water areas, there were many small species, such as the faucet snail and various species of insect larvae, including the midge larvae [2, 3].

GLACIAL RELICT

Species that was already around after the last ice age approximately 12,000 years ago.

Diatoms and zoobenthos also affect one another. Large diatoms are an easy takeaway meal for zoobenthos. The high number of zoobenthic species in salty areas is likely to reduce the number of large diatom species. Due to this, diatom communities in salty areas mainly consist of small and low diatom species, because the large ones are eaten by zoobenthos.

WHAT DO OUR FINDINGS MEAN FOR THE FUTURE?

Saltiness is one of the most important factors determining where underwater organisms can live. In the future, climate change may alter the saltiness of oceans, especially in areas close to coasts where rivers bring fresh water from land to the ocean. This means that species that we are used to seeing at our favorite beach may not survive there anymore and may be replaced by new species that are adapted to the new saltiness. At the same time, the functioning of the whole ecosystem may change, because the new species may do their job differently than the ones they replaced.

We all can still help our precious oceans to stay healthy and functioning. We can clean up the beach, we can use less plastic to make less ocean debris, and we can reduce our carbon footprint by walking and riding a bike instead of taking a car. And most importantly, we can learn to understand our oceans better, because we will love only what we understand and conserve only what we love.

ACKNOWLEDGMENTS

This study was supported by the Walter and Andrée de Nottbeck Foundation (grants to LV and AV), the Sophie von Julin Foundation (AV and AN), Societas pro Fauna et Flora Fennica (LV), the Finnish Society of Sciences and Letters (LV), the Sakari Alhopuro Foundation (LV), the Academy of Finland (Decision 323212; AV), and the University of Helsinki three-year research grant (AV). We would like to thank Johanna Gammal for drawing the map of the Baltic Sea.

ORIGINAL SOURCE ARTICLE

Virta, L., Soininen, J., and Norkko, A. 2020. Diversity and distribution across a large environmental and spatial gradient: evaluating the taxonomic and functional turnover, transitions and environmental drivers of benthic diatom communities. *Global Ecol. Biogeogr.* 29:2214–2228. doi: 10.1111/geb.13190

REFERENCES

1. Villnäs, A., and Norkko, A. 2011. Benthic diversity gradients and shifting baselines: implications for assessing environmental status. *Ecol. Appl.* 21:2172–2186. doi: 10.1890/10-1473.1
2. Bonsdorff, E. 2006. Zoobenthic diversity-gradients in the Baltic Sea: continuous post-glacial succession in a stressed ecosystem. *J. Exp. Mar. Biol. Ecol.* 333:383–391. doi: 10.1016/j.jembe.2005.12.041
3. Ojaveer, H., Jaanus, A., MacKenzie, B.R., Martin, G., Olenin, S., Radziejewska, T., et al. 2010. Status of biodiversity in the Baltic Sea. *PLoS ONE* 5:e12467. doi: 10.1371/journal.pone.0012467
4. Remane, A. 1934. Die Brackwasserfauna. *Verandlunge der Deutschen Zoologischen Gesellschaft.* 36:34–74.

SUBMITTED: 27 February 2023; **ACCEPTED:** 26 December 2023;
PUBLISHED ONLINE: 18 January 2024.

EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Barbara Pivato and Alejandro Acevedo-Gutierrez

CITATION: Virta L, Norkko A and Villnäs A (2024) Salty, Brackish, Or Fresh—Saltiness Matters for Aquatic Species! Front. Young Minds 11:1175170. doi: 10.3389/frym.2023.1175170

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

ETHAN, AGE: 11

My name is Ethan. I play the piano and take martial arts classes. I like video games and to read. My favorite thing to do is hang out with my friends, play video games, and read. I have a one-eyed pug named Loki. I love sharks and when I am older, I want to be a conservation biologist and swim with sharks.

LORENZO, AGE: 12

I am a sports enthusiast who is into everything from football to judo. Recently, I have been competing in judo since last year. I am not just muscles, I am good in math and physics at school. However, what I cherish the most is hanging out with my friends and having a good time together. Chess is another interest of mine. My mum is my favorite opponent, but let us be real, I have got her in checkmate more times than I can count!

PAOLO, AGE: 9

I am genuine curious and have a deep love for observing nature: plants, animals, fungi, and more. What intrigues me the most are insects; I am even comfortable capturing spiders with my bare hands! I bring various types of insects at home, much to the delight of my mum. As a birthday present, I received a terrarium, which I now use to spend hours observing my collection of insects. My dream is to become a scientist or a veterinarian.

AUTHORS

LEENA VIRTA

Leena Virta is a researcher who focuses on investigating microbes on the seafloor and how they affect ecosystem functioning. *leena.virta@helsinki.fi

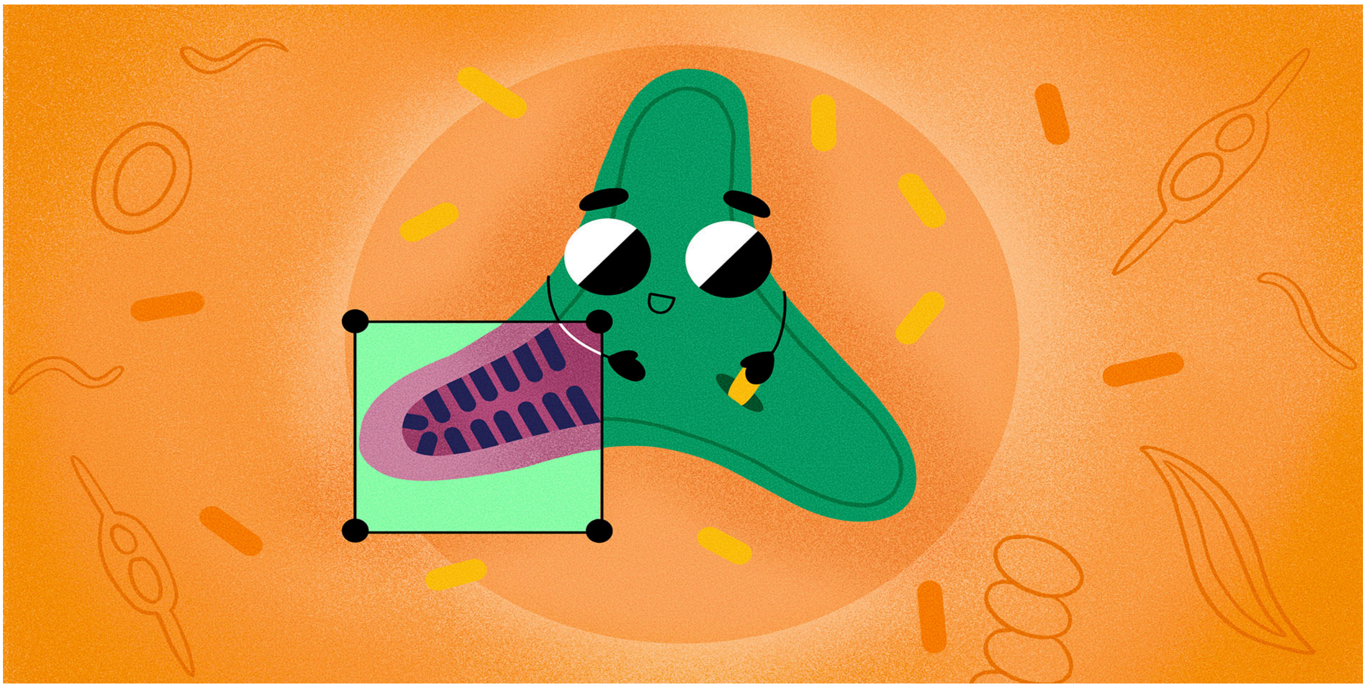
ALF NORKKO

Alf Norkko is an ecologist who works with marine ecosystems. His research focuses on understanding how biodiversity and climate change work together in affecting coastal ecosystems.

ANNA VILLNÄS

Anna Villnäs is a marine benthic ecologist who explores how disturbances affect seafloor biodiversity and ecosystem functions.

EARTH SCIENCES
Published: 08 January 2024
doi: 10.3389/frym.2023.1175538



DID ALGAE EAT ALL THE SILICA IN THE WORLD'S OCEANS?

***Rebecca A. Pickering**† and Kristin Doering*†**

Department of Geology, Lund University, Lund, Sweden

†These authors have contributed equally to this work

YOUNG REVIEWERS:

ANTONIO
AGE: 10

UMBERTO
AGE: 14

Silicon is a crucial nutrient that can join with the element oxygen to form a substance commonly called silica. Silica, commonly known as glass, is found in rocks in the Earth's crust and dissolves into the oceans, where organisms like algae and sponges use it to build their glassy skeletons. This process, called biosilicification, is extremely important in the silica cycle. Over time, organisms have changed the silica cycle. Today, because of these organisms, the oceans no longer contain much silica. However, when the Earth was younger and these organisms had not evolved yet, no biological processes affected silica in the oceans. The evolution of these oceanic organisms across time has removed silica from the oceans. In this article, we discuss how the evolution of silicon-using sponges, as well as tiny organisms called zooplankton and algae, have changed the amount of silica in the world's oceans through geologic time.

IMPORTANCE OF SILICA IN THE OCEANS

Silicon is one of the most common elements on Earth. Silicon can join with the element oxygen to form silicon dioxide, commonly called **silica**. You probably already know what silica looks like, as it goes by a much more common name—glass. Silica is one of the most common chemicals found in solid rocks and minerals in the Earth's crust and mantle. Over time, the rocks and minerals on Earth break down into smaller pieces due to wind or rain, in a process called weathering. Eventually, the silica pieces get so small that they dissolve into nearby rivers and streams. From there, the dissolved silica moves into the world's oceans. Rivers across the globe put a lot of dissolved silica into the oceans every minute of every day. These transformations from solid into liquid form are an important part of the **silica cycle**, which tracks how silica moves throughout the earth. Dissolved silica in the oceans is an important nutrient for many ocean-dwelling creatures, such as microscopic algae and sponges (Figure 1). These organisms eat up the dissolved silica in seawater to build their skeletons, the same way humans use calcium to build strong bones. A glass skeleton is stronger than you might think, and hard for predators to break, so it is good protection for ocean creatures. The process by which organisms turn dissolved silica in seawater into a glass skeleton is called **biosilicification**.

SILICON

The second most common element in the Earth's crust. Silicon is found in most rocks, sands, clays, and soils. Its atomic number is 14, and the symbol is Si.

SILICA

A chemical compound made up of silicon and oxygen. It occurs in various forms (as in quartz, opal, and sand) and is an important part of glass, concrete, and porcelain.

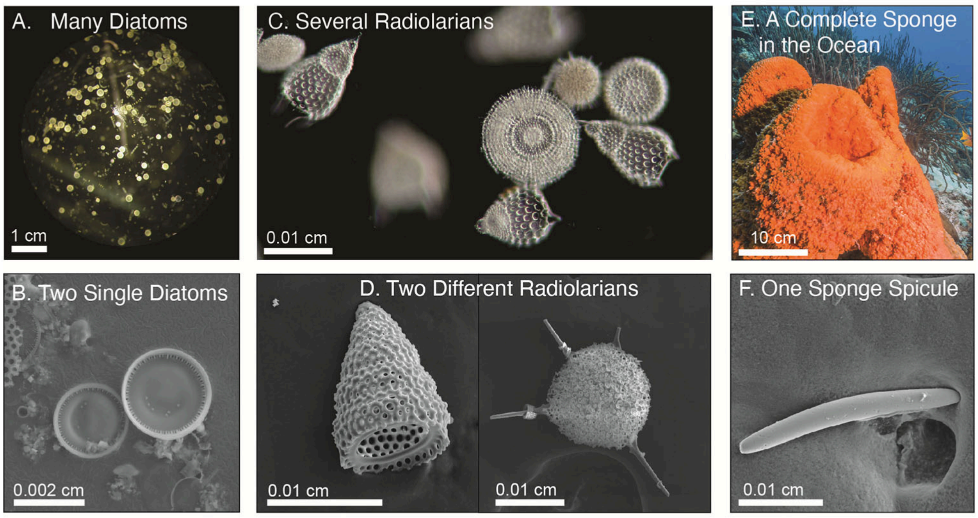


Figure 1

Figure 1

What does a glass skeleton look like? Several types of ocean organisms have skeletons made of silica, including diatoms, radiolarians, and sponges. **(A)** A microscopic image of many diatoms. **(B)** Two single diatoms, close-up. **(C, D)** Radiolarians. **(E)** Sponges are much larger, so they can be seen without a microscope. **(F)** Have you ever wondered what a sponge skeleton looks like? Here is what a piece of sponge skeleton, called a spicule, looks like under a microscope. Scale bars help to show how big each organism is.

Today's oceans are full of tiny algae made of glass skeletons called diatoms (Figures 1A, B). Diatoms may only be between 0.002 and 0.02 cm in size, but they remove a large amount of the dissolved silica from ocean water to build their skeletons. Diatoms like to stay near the surface of the seawater because, like most plants, they need sunlight to perform **photosynthesis** and survive. When diatoms perform photosynthesis, they remove carbon dioxide—a greenhouse gas—from our atmosphere. Since diatoms need silica, this means that the amount of carbon dioxide in Earth's atmosphere is indirectly related to the amount of dissolved silica in seawater.

Without a high-powered microscope, you cannot see an individual diatom, but they are an important food source for animals like **zooplankton** and fish. Zooplankton are a critical part of the marine food web, as they move energy up the food chain into organisms that larger predators, like humans, like to eat. The flow of energy from phytoplankton to zooplankton to fish is one of the most important processes in the ocean today.

There are also some types of zooplankton, called radiolarians (Figures 1C–E), that like to build their skeletons out of silica. These glass zooplankton are a little bigger than diatoms (between 0.003 and 0.3 cm in size), but you still need a microscope to see them. Finally, some sponges (Figures 1F, G) use dissolved silica in the seawater to build their skeletons out of glass, but they live on the seafloor, far away from the algae and zooplankton hanging out at the ocean surface. Most sponges are only a few centimeters in size, but some can grow up to two meters in length.

These three groups of creatures—diatoms, zooplankton, and sponges—need a lot of silica to build their skeletons. This means that today's oceans do not have a lot of dissolved silica in them. However, when the Earth was younger, these organisms were not living in the oceans yet, so there was a lot more dissolved silica around. Over time, the evolution of algae, zooplankton, and sponges has removed silica from the oceans. Researchers have only been trying to understand the ocean's silica cycle for about 34 years [1–3], and in that time a lot of progress has been made toward understanding how silica levels in the world's oceans got to where they are today [4, 5]. Researchers agree that biosilicification is what has driven the change in the silica cycle over time.

PRECAMBRIAN TIMES (540 MILLION YEARS AND OLDER)

The Precambrian times cover most of the Earth's history, from the creation of the planet 4.5 billion years ago to the emergence of complex life forms almost 4 billion years later. During Precambrian times, Earth had little to no life in its oceans (Figure 2). Therefore, the silica cycle was only controlled by forming silica-rich rocks called **chert**. Chert is a very hard rock that forms when there is so much dissolved silica in the oceans that the silica turns back into a solid form again. Have you ever made rock candy? If you try to dissolve a really large amount of sugar in water, it starts to form hard candy crystals. Similarly, if there is too much dissolved silica in ocean water, it starts to form solid rock crystals. In prehistoric times, people used chert to make arrowheads and hand axes because chert is very hard

SILICA CYCLE

A cycle that uses biology, geology, and chemistry to track the movement of solid and liquid silica between the Earth's different systems (like when it moves from the land into the ocean).

BIOSILIFICATION

The process by which organisms use dissolved silica to form solid silica, generally to build their skeletons.

PHOTOSYNTHESIS

A process by which plants/algae produce oxygen and food for themselves and other organisms, using sunlight and carbon dioxide.

ZOOPLANKTON

Small animals in the plankton group. Plankton are aquatic organisms that cannot swim effectively but instead drift with water currents.

CHERT

A sedimentary rock rich in silica. It breaks up into pieces with sharp edges which is why it was used by people to make weapons and tools.

and sharp when broken. Have you seen a chert tool? Maybe the rock it was made from came from the ocean floor during Precambrian times, when the amount of dissolved silica in the ocean was high because there were no creatures around to eat up all the tasty, dissolved silica floating around.

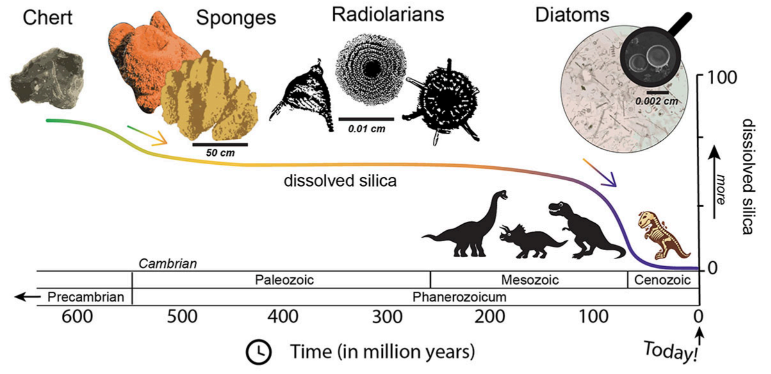


Figure 2

Figure 2

Who is eating all the silica? The amount of dissolved silica in the oceans has changed since the early Earth. After chert formation and the evolution of sponges and radiolarians, the amount of dissolved silica in the oceans has decreased. Researchers believe that diatoms have been eating most of the silica since the end of the Mesozoic, which is around the same time that dinosaurs went extinct. Scale bars help to show how big each organism is.

CAMBRIAN TIMES (540 MILLION YEARS AGO): SPONGES AND ZOOPLANKTON ARRIVE ON THE SCENE

You probably think of a sponge as a soft, porous, squishy material used when you are cleaning the house. Sponges are actually animals, and they come in many varieties. Some of them use silica to build their skeletons. Sponges are likely some of the first animals that evolved on Earth. Although not all sponges are still around today, we know that sponges in the Cambrian (at the beginning of the Paleozoic) were the first animals to remove dissolved silica from ocean water to build their skeletons. Researchers observed that, as sponge populations began to increase, the thick layers of silica-rich chert became less common. This tells us that sponges directly impacted the amount of dissolved silica in the oceans.

Just after the appearance of the first sponges, a group of zooplankton called radiolarians appeared as well. While sponges prefer to sit on the ocean floor, radiolarians drift in the seawater. Their populations quickly grew larger, and during the Ordovician (485 million years ago), radiolarians expanded across the globe, resulting in an overall decrease in the amount of dissolved silica in the oceans (Figure 2). Rocks and minerals in the Earth's crust and mantle continued to dissolve, but organisms were removing a large amount of dissolved silica from the water for the first time. Sponges and radiolarians controlled levels of dissolved silica in the oceans for several million years.

MESOZOIC (250 MILLION YEARS AGO): DIATOMS TAKE OVER!

The Mesozoic was the time when the dinosaurs lived. The Mesozoic includes the Triassic, Jurassic, and Cretaceous Periods—names that might be familiar to you. Did you know that, while dinosaurs roamed the Earth and swam in the seas, something more important was evolving? The Mesozoic saw a huge change in the ocean ecosystem. For the first time, many groups of phytoplankton algae appeared. One group, the diatoms, thrived. As diatoms used silica to build their skeletons, dissolved silica was rapidly reduced in the world's oceans. Over time, the number of algae in the oceans quickly increased, and dissolved silica was rapidly removed (Figure 2). Algae now controlled the dissolved silica cycle in the oceans and, as their population grew, they kept eating. Diatoms retained control of the silica cycle for the next 200 million years.

TODAY'S OCEANS: IS ANY SILICA LEFT OVER?

The amount of dissolved silica in the oceans today is still largely controlled by algae. Things like ocean circulation and the newly dissolved silica entering the ocean from rocks and minerals can change on occasion, but overall, once dissolved silica enters the ocean, algae quickly eat it up from the surface waters. Changes in human activity are impacting how much dissolved silica enters the oceans. For example, building dams can reduce dissolved silica input, while eutrophication can impact how much silica is eaten by the algae. Further, as the environment warms, warmer ocean temperatures can affect how many algae grow, which in turn impacts the silica cycle. While there are now more ocean creatures that eat dissolved silica, the three main groups we discussed still largely control the amount of dissolved silica in our oceans. Understanding how these groups evolved over time helps us better understand how our environment will change in the future.

ACKNOWLEDGMENTS

This abstract is part of a series of 6 manuscripts about the marine silicon cycle put together by the ECR SILICAMICS group and validated by Hedwig Ens, Senior Journal Specialist. We thank the SILICAMICS ECRs consortium for its enthusiasm for putting this project together.

REFERENCES

1. Siever, R. 1991. "Silica in the oceans: biological-geochemical interplay," in *Scientists on Gaia*, eds S. H. Schneider, and P. J. Boston (Cambridge, MA: MIT

Press). p. 287–95.
2. Siever, R. 1992. The silica cycle in the Precambrian. *Geochim. Cosmochim. Acta* 56:3265–72. doi: 10.1016/0016-7037(92)90303-Z
3. Maliva, R. G., Knoll, A. H., and Siever, R. 1989. Secular change in chert distribution: a reflection of evolving biological participation in the silica cycle. *Palaios* 4:519. doi: 10.2307/3514743
4. Conley, D. J., Frings, P. J., Fontorbe, G., Clymans, W., Stadmark, J., Hendry, K. R., et al. 2017. Biosilicification drives a decline of dissolved si in the oceans through geologic time. *Front. Mar. Sci.* 4:397. doi: 10.3389/fmars.2017.00397
5. Trower, E. J., Strauss, J. V., Sperling, E. A., and Fischer, W. W. (2021). Isotopic analyses of Ordovician–Silurian siliceous skeletons indicate silica-depleted Paleozoic oceans. *Geobiology* 19:460–72. doi: 10.1111/gbi.12449

SUBMITTED: 27 February 2023; **ACCEPTED:** 15 December 2023;
PUBLISHED ONLINE: 08 January 2024.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Elisa I. García-López and Kellie Aldi

CITATION: Pickering RA and Doering K (2024) Did Algae Eat All the Silica in the World'S Oceans? Front. Young Minds 11:1175538. doi: 10.3389/frym.2023.1175538

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

ANTONIO, AGE: 10
Antonio enjoys science in general, but really loves learning about interesting animals and plants. In his spare time, Antonio also enjoys playing soccer and chess.

UMBERTO, AGE: 14
Hi, I have just turned 14 and I am starting high school next year. I really like the sciences, and I think I will be a botanist because I like plants and nature a lot. I love flowers and seeing how nature changes, but in high school I will study classical because history, art, Latin and Greek intrigued me a lot. I like playing electronic

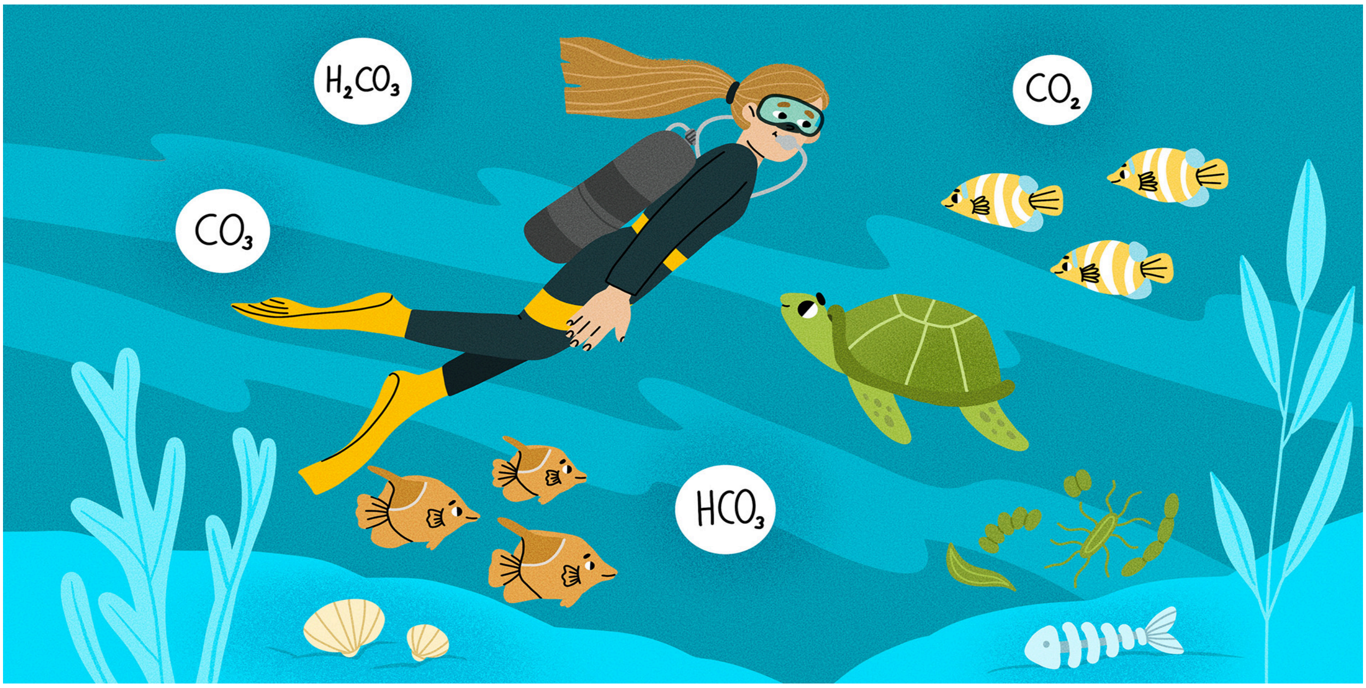
games, drawing and going for walks with friends as well as going to the beach. I am a cook and I prepare many dishes for my family such as spaghetti carbonara, pizza as well as Chinese and Japanese recipes.

AUTHORS

REBECCA A. PICKERING
I am a marine biogeochemist working to investigate the interactions between biology, silicon processes and the environment. Currently, I focus on what happens to all types of silica skeletons when they are buried in the sediments after they die throughout the Earth's history. My research interests include: global and local silicon cycling, stable and radioactive silicon isotopes, the formation of new biogenic silica skeletons and how they dissolve in the ocean after they die, weathering processes, silica authigenesis, and how silica sediments can remove other elements from the oceans. *rebecca.pickering@geol.lu.se

KRISTIN DOERING
I am a marine biogeochemist and micropalaeontologist. I work on discovering how the ocean's nutrient cycle has changed in the past. To do so, I look at different microfossils, such as diatoms, radiolarians, and sponge spicules. The chemical properties of these organisms compared to today's seawater tell me how much nutrients there were in the past ocean and how much of it was used. I am fascinated by studying microfossils as they can tell us so much about the past, and I am constantly working to improve our understanding of them.

EARTH SCIENCES
Published: 03 January 2024
doi: 10.3389/frym.2023.1150384



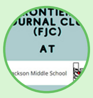
A SEA OF CARBON

***Lumi Haraguchi*[1*], *Rafael Gonçalves-Araujo*[2] and *Colin A. Stedmon*[2]**

[1] *Research Infrastructure Unit, Finnish Environment Institute, Helsinki, Finland*

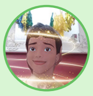
[2] *Section for Oceans and Arctic, National Institute of Natural Resources, Technical University of Denmark, Lyngby, Denmark*

YOUNG REVIEWERS:



JACKSON FRONTIERS REVIEW CLUB

AGES: 12–13



NOAH

AGE: 10

There is more to the sea than what you can see! Did you know that when you swim in the sea, you are actually swimming in a soup of carbon? The ocean has many carbon-containing things. Some are large like fish, whales, and shells, but most of them are too small to be seen unless we use microscopes. Some of these minuscule particles are living organisms, while the rest are their remains as they decompose. When land creatures die, they decompose into soil. In the ocean, creature remains are gradually dissolved in seawater. All this dead material contains the element carbon, which, at some point in time, was carbon dioxide in the air. The ocean stores a large portion of the carbon on our planet. In this article, we explain how all this carbon ends up in the ocean and how human activities affect the carbon cycle in the sea.

WHY IS CARBON SO IMPORTANT?

Carbon is the element of life. There are no other elements that have just the right properties for the job. Carbon can bind to many other elements, such as hydrogen, nitrogen, oxygen, phosphorus, and more. This means carbon can help to build a wide variety of molecules, all with very different properties. Some examples are hard, rigid structures such as carbonates, which many corals and shells are made of; flexible fibers in plants, which we can turn into cloth or rope; and sugars, such as those that give honey and soft drinks a sweet taste. Look around and you will see that carbon is everywhere, in your home and outdoors. The ocean covers $\frac{3}{4}$ of the Earth's surface, so it may come as no surprise that it also contains a large amount of carbon. So, let us find out what shapes and forms ocean carbon is in, and why we even need to think about them.

IS ALL THE CARBON THE SAME?

Carbon atoms in the ocean are always attached to other carbon atoms and atoms of other elements, forming a wide range of substances. Even though we do not know what all the carbon-containing substances are, we can still describe them based on their properties—for example, whether they sink or float and what other elements they consist of. If they are big enough to sink, we refer to them as particles. Some particles are so small that we need a microscope to see them. The substances that are too small to sink are called **dissolved** substances. If a substance is made of carbon atoms attached to other carbon atoms or hydrogen atoms, we refer to it as **organic substance** (even when atoms of other elements are present). The soft parts of all organisms (including you) such as skin, muscle, and organs, are made of organic substances. All other carbon-containing substances are called inorganic. Carbon-containing rocks such as those that make marble and chalk are examples of inorganic carbon substances, as they contain carbon attached to oxygen and calcium atoms (calcium carbonate, $CaCO_3$). Carbon dioxide (CO_2) in the atmosphere is an example of an inorganic carbon substance that is a gas (Figure 1).

DISSOLVED

When a substance breaks down to smaller units, which do not sink, and is incorporated into a liquid, forming a solution.

ORGANIC SUBSTANCE

Is a kind of chemical containing carbon atoms attached to other carbon or hydrogen atoms.

Using these two properties, we can group carbon into four categories: **particulate** organic, particulate inorganic, dissolved organic, and dissolved inorganic (Figure 2). Most of the carbon in the ocean is dissolved inorganic carbon. In fact, the ocean has removed a large portion of the CO_2 we have released into the atmosphere, by dissolving it (see this Young Minds article for some examples). Organisms in the ocean control the balance between organic and inorganic carbon, and between particulate and dissolved carbon. All organisms, from the tiniest bacteria to the largest whales, consist of organic carbon, so we classify all organisms as particulate organic carbon. Some organisms also have body parts that are made of carbonates and therefore contribute to particulate inorganic carbon. The last form of carbon to consider is dissolved organic carbon, which includes all organic particles that gradually leak into seawater (even from your body when you take a swim). When there are very high

PARTICULATE

Refers to particles in suspension in the water, including both living and non-living substances that can sink.

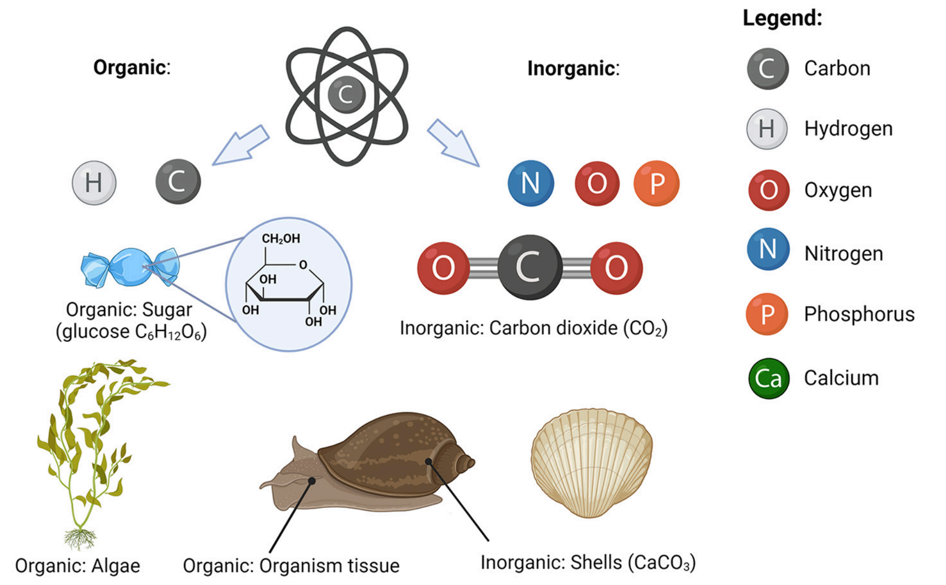


Figure 1

Figure 1

Carbon can attach to various elements to form organic and inorganic substances. Organic substances contain carbon attached to other carbon (C) or hydrogen (H) atoms. Inorganic substances contain carbon attached to any other element, such as oxygen (O), nitrogen (N), or phosphorus (P)(image created with BioRender.com).

concentrations of dissolved organic carbon, the water often has a brown/yellow color (see this Young Minds article for some examples). Perhaps you have seen something similar happening when you make a cup of tea. The hot water in your teacup dissolves some of the organic carbon in the tea leaves, and the water turns brown.

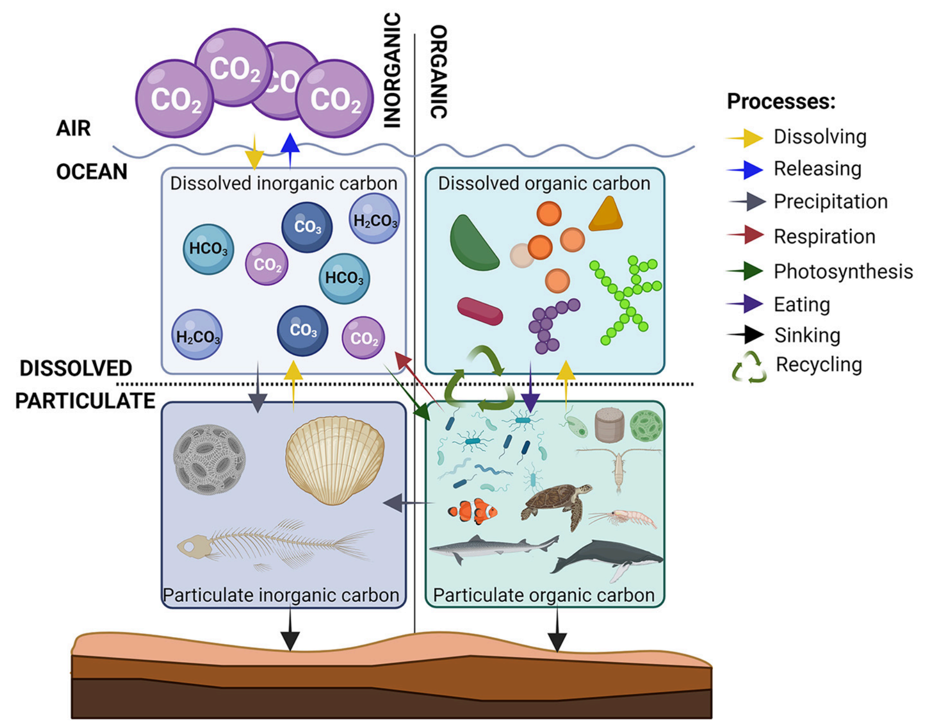


Figure 2

Figure 2

What happens to the carbon in the ocean? Carbon can be found in 4 forms in the ocean. The amount of carbon in each form varies, and carbon in one form can change to another form through various processes, which are shown by the colored arrows (explained in the list on the right) (image created with BioRender.com).

OCEAN CARBON CYCLE

Is how carbon atoms travel from the atmosphere into organisms in the Ocean and then back into the atmosphere, again and again.

GRAZERS

Predators that consume plants and algae.

RESPIRATION

The process of obtaining energy by breaking sugar molecules apart using oxygen. It is done by all living organisms and produces CO_2 and water as waste products.

PHYTOPLANKTON

Minuscule algae that can make their own food using CO_2, water, and sunlight.

MICROBIAL LOOP

Is how carbon and other nutrients are processed by the smallest organisms (such as bacteria and phytoplankton) in the Ocean.

THE OCEAN AS A CARBON RECYCLER

In the ocean, carbon is constantly being moved between these four forms and this movement makes up the **ocean carbon cycle** (Figure 2). A balanced carbon cycle is essential for controlling Earth's climate and the diversity of organisms on the planet. The ocean carbon cycle consists of a collection of processes that transform carbon from one form to another. Scientists have found that all these processes are affected by changes in the concentration of CO_2 in the air, which is increasing due to human activities. So, the balance between the various forms of carbon is changing. CO_2 can be dissolved in or released from seawater, depending on the concentrations of CO_2 in the water and in the air. If the concentration in the air is higher than in seawater, carbon dissolves into the ocean. However, CO_2 can be released from the ocean to the air if the concentration in the sea is higher. As the concentration of CO_2 in the air has increased over the last 100 years, the ocean has dissolved more and more CO_2.

Through photosynthesis, algae and aquatic plants use the sun's energy to produce organic carbon substances from dissolved inorganic carbon (see this Young Minds article for some examples). From here, the carbon can go four ways:

1) When algae and aquatic plants are eaten by **grazers**, some of the particulate organic carbon is transformed into new cells (just as we grow when we eat), so it stays as organic particles but often becomes bigger ones, starting a food web.
2) **Respiration** by organisms turns some of the particulate organic carbon back into dissolved inorganic carbon. The energy stored in organic substances is used by the organisms and the carbon is released as CO_2, which is what happens when we breathe out.
3) Organisms die and sink to the sea floor, to be slowly buried. They form rocks and oil, and this carbon is stored underground for millions of years.
4) Particulate organic carbon releases dissolved organic carbon as the organism's cells leak or fall apart, spilling their contents into seawater.

Some of the dissolved organic carbon substances from leaking or dead cells are food for bacteria living in seawater (Figure 3). This recycles some of the carbon, either back to dissolved inorganic carbon or into particulate organic carbon, where it contributes once more to the food web. This cycling of carbon between organic and inorganic, and between particulate and dissolved, is mainly done by microscopic organisms such as bacteria, **phytoplankton**, and small grazers, and is therefore called the **microbial loop** (see this Young Minds article for some examples) [1]. When you think of life in the ocean, your first thought might be fish, sharks, and whales. Even though they are large, these animals represent only a very small portion of the carbon in the ocean. Most of it is "spinning" around in the microbial loop.

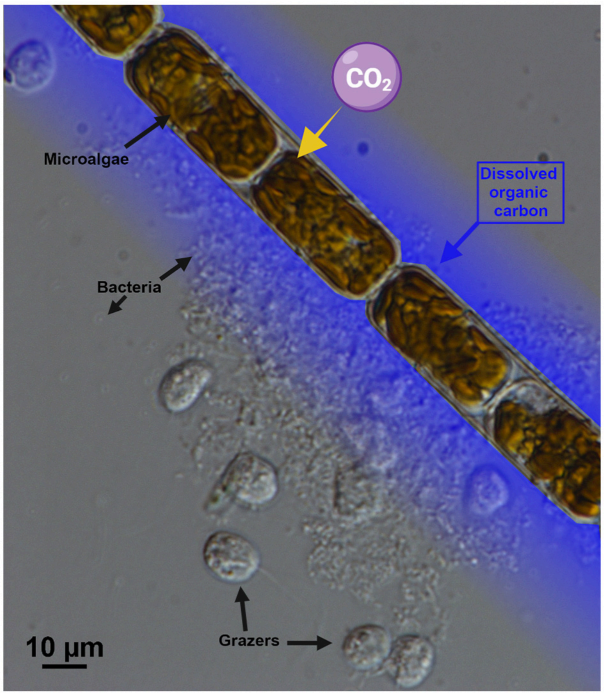


Figure 3

Figure 3

A photograph, taken using a microscope, showing microalgae surrounded by bacteria (tiny gray dots) and other organisms that feed on the bacteria (larger, roundish, gray forms). The microalgae release dissolved organic carbon (represented by the blue shading), which helps bacteria to grow. The scale bar at the bottom represents 10 µm. A human hair is about 70 µm thick (photo credit: L. Haraguchi).

Bacteria are carbon-recycling champions, but they cannot use all the dissolved organic carbon in the sea. Like us, they can also be picky eaters, selecting the organic substances that they like best [2]. Eventually, the remaining substances may accumulate as "leftovers" from the ocean buffet. If this is true then this could be a new way in which the ocean ecosystem can help reduce the amount of CO_2 in the air and store it as dissolved organic carbon [3].

A CHANGING CARBON CYCLE

It is important to understand how much carbon is in the ocean, what form it exists in, and what processes are transforming it. Once we know this, we can try to predict how the world may change in the future.

What happens when CO_2 increases? Will the carbon shown in the four boxes in Figure 2 increase as well? The answer is... it depends! More CO_2 in the ocean might affect not only the size but also the contents in each box. For the particulate organic carbon box, more CO_2 will influence the number of organisms (the box size) and which types of organisms are there. This happens because some organisms like more CO_2 than others do, so they thrive under these new conditions. A similar change can happen if temperatures change. Some organisms like it hot, and others do not. This is important because the presence of different kinds of organisms changes the food web and affects how carbon travels within the carbon cycle.

One challenge is that particulate organic carbon exists as many different life forms, and dissolved organic carbon is in so many kinds of substances that we cannot identify them all. Without such basic information, it becomes harder to understand the processes of the carbon cycle and how they relate to other factors, such as temperature changes.

ACKNOWLEDGMENTS

LH received funding from Academy of Finland grant agreement No. 342223. RG-A has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Grant Agreement No. 839311. CS has received funding from the Independent Research Fund Denmark Grant No. 9040-00266B. This work was partly funded by the European Union H2020 as part of the EU Project ARICE grant agreement no. 730965 through the project NoTAC ("Novel Tracers of Arctic Carbon and water exchange in the Fram Strait").

REFERENCES

1. Azam, F., Frenzel, T., Field, J. G., Gray, J. S., Meyer-Rell, L. A., and Thingstand, F. 1983. The ecological role of water-column microbes in the sea. *Marine Ecol. Prog. Ser.* 10:257–63. doi: 10.3354/meps010257
2. Hansell, D. A. 2013. Recalcitrant dissolved organic carbon fractions. *Ann. Rev. Mari. Sci*. 5:421–45. doi: 10.1146/annurev-marine-120710-100757
3. Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., et al. 2010. Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nat. Rev. Microbiol*. 8:593–9. doi: 10.1038/nrmicro2386

SUBMITTED: 24 January 2023; **ACCEPTED:** 08 December 2023;
PUBLISHED ONLINE: 03 January 2024.

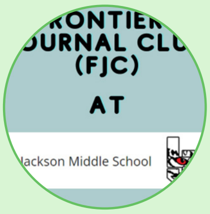
EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Soumya Kini and Christopher Poonian

CITATION: Haraguchi L, Gonçalves-Araujo R and Stedmon CA (2024) A Sea of Carbon. Front. Young Minds 11:1150384. doi: 10.3389/frym.2023.1150384

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



JACKSON FRONTIERS REVIEW CLUB, AGES: 12–13

We are a group of 12 and 13 year olds that are part of the Frontier Journal Club at our local public middle school. We love to talk about science, learn about what is going on in our world, and what we can do to make it better for all of us.

NOAH, AGE: 10

I live on a small island that has been designated a UNESCO Biosphere Reserve. I am most interested in biodiversity and nature and my favorite animals are salamanders like axolotls and olms. I go to a very small school with less than 20 students in the whole school. My favorite sports are basketball and taekwondo and I enjoy reading in my spare time. I speak Spanish and English.

AUTHORS

LUMI HARAGUCHI

Dr. Lumi Haraguchi is an oceanographer from Brazil. She obtained her Ph.D. from Aarhus University (Denmark) in 2018. For Lumi, studying the smallest algae in the sea was the perfect way to combine her interest in plants with her love for the sea. Her work focuses on improving our understanding of the role of small organisms in the carbon and nutrient cycles, and how those cycles are affected by changes in the environment. Lumi feels that working as scientist is very rewarding, providing opportunities to keep learning new things and to travel to many places. *lumi.haraguchi@syke.fi

RAFAEL GONÇALVES-ARAUJO

Dr. Rafa Gonçalves-Araujo is a Brazilian oceanographer who got his Ph.D. in natural sciences from the University of Bremen (Germany) in 2016. Rafa has been fascinated by the ocean since the first time he saw it in his childhood. He studies the carbon cycle with a focus on the Arctic Ocean. In his research, he tries to solve this puzzle by combining samples collected directly from the ocean with satellite remote sensing. Apart from enjoying being on expeditions to collect water samples, his work also involves lab work, scientific instrumentation, and a lot of time in front of the computer.

COLIN A. STEDMON

Prof. Colin Stedmon is a chemical oceanographer at the Technical University of Denmark. He obtained his Ph.D. from the University of Copenhagen in 2004. His current research focuses on Arctic marine biogeochemistry. This essentially involves studying the chemical composition of seawater and collaborating with experts in marine physics and biology to understand how the oceans function and, in particular, how the Arctic is changing. He mostly enjoys the detective work—looking for patterns in the data he collects, finding explanations for what the data show, and contributing to an understanding of how the oceans function.

EARTH SCIENCES
Published: 14 December 2023
doi: 10.3389/frym.2023.1176653

DIATOMS LIKE IT LIGHT! HOW DIATOM EATING HABITS HELP US UNDERSTAND THE PAST OCEAN

Ivia Closset [1,2*†], ***Kristin Doering*** [3*†] ***and Bianca T. P. Liguori*** [4†]

[1] *Marine Observatories and Measurement Techniques, Finnish Meteorological Institute, Helsinki, Finland*
[2] *Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA, United States*
[3] *Department of Geology, Lund University, Lund, Sweden*
[4] *Marine Isotope Geochemistry, Institute for Chemistry and Biology of the Marine Environment (ICBM), University of Oldenburg, Oldenburg, Germany*

[†] *These authors have contributed equally to this work*

YOUNG REVIEWERS:


HELENA,
MOMO,
TATI
AGES: 11–12


JUDE
AGE: 15

Have you ever wondered if today's oceans were different millions of years ago? Well, a group of small algae called diatoms can help us to find this out. Diatoms build a strong glass skeleton, like a shell, which can last for thousands and even millions of years after their deaths. To build their glass skeletons, diatoms take up silicon from the seawater, similar to us eating food to build our bodies. Diatoms preferentially use one type of silicon in their menu, leaving behind the type they do not like. Researchers can track this eating habit by measuring the proportion of the two types of silicon stored within diatoms. Using this silica-print like a fingerprint, scientists can investigate what the surface ocean was like, how much diatoms were eating silicon, and how these organisms have affected Earth's past climate.

WHAT ARE DIATOMS AND WHY ARE THEY IMPORTANT FOR THE CLIMATE?

Diatoms are tiny algae that live almost everywhere near the surface of oceans, lakes, and rivers. They stay near the surface because, just like any plant, they need light to produce energy through the process of **photosynthesis** (for more information about photosynthesis in the oceans, see this Frontiers for Young Minds article). To grow, diatoms also need nutrients, which are the equivalent of the food we eat.

PHOTOSYNTHESIS

A process by which plants/algae produce oxygen and food for themselves and other organisms using sunlight and CO_2.

Unlike our bones, the skeletons of diatoms are outside their bodies, like a shell, and they are made of silica (also called opal), which is the same material we use to make glass. Therefore, diatom skeletons are transparent. When diatoms die, they sink to the bottom of the ocean, carrying with them all the CO_2 they used to grow and create their skeletons while they were alive (Figure 1C) [1]. Therefore, diatoms are very important players in **climate** regulation, because they remove CO_2 from the air, which helps to reduce climate change. On the seafloor, the opal skeletons do not fall apart easily and can remain buried for millions of years. Through this process, diatoms are responsible for up to 40% of the carbon removed from the atmosphere by the oceans.

CLIMATE

The average long-term pattern of weather in a region across the Earth.

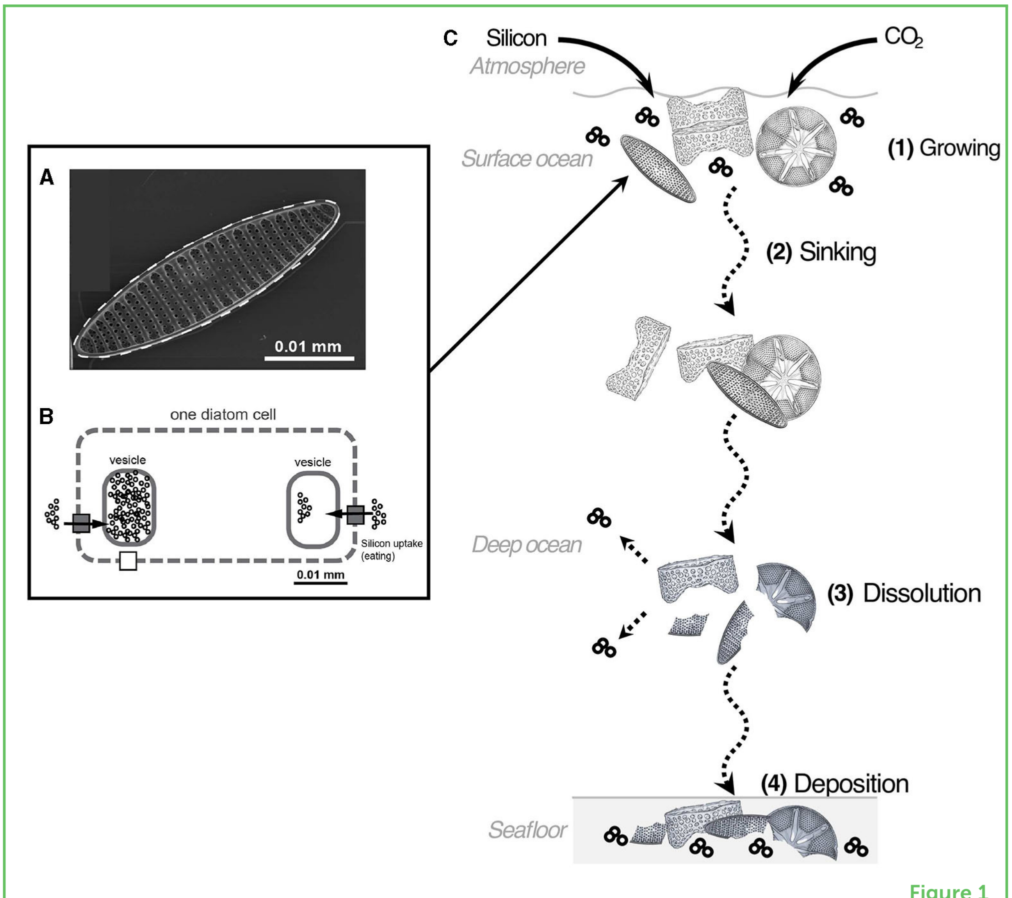


Figure 1

Figure 1

(A) A diatom seen through a microscope. **(B)** Silicon enters the diatom cell and is collected in vesicles, where it is transformed into opal crystals. The opal crystals form the diatom's skeleton (gray dashed line). **(C)** At the ocean's surface, diatoms take up CO_2 and silicon and use light to grow. When they die, they sink and carry the CO_2 and silicon into the deep ocean. Parts of the skeleton dissolve, releasing CO_2 and silicon back into the water. Undissolved pieces remain on the seafloor, where they can store carbon (from CO_2) and silicon for a very long time.

Diatoms are so tiny that you need a microscope to see them (Figure 1A). Only the biggest can reach a length of 0.5 mm and are about as wide as one of your hairs. By collecting samples from the seafloor, scientists can find diatom skeletons and use those skeletons to gather information about ocean conditions in the past and present. This research field is called **paleoceanography**.

PALEOCEANOGRAPHY

The study of past ocean conditions.

HOW DO DIATOMS BUILD THEIR GLASSY SKELETONS?

To build their skeletons, diatoms need silicon, which they find dissolved in seawater. They store this silicon in small pockets called **vesicles** inside their bodies, where they can transform the silicon into small opal crystals (Figure 1) [2]. They use these opal crystals to build their skeletons, which are decorated with spines and holes. In some places, diatoms use all the silicon from surface water, leaving nothing behind. We know that they do so because scientists have found a way to track their fingerprints—or should we say their silicon-prints—in the ocean and on the seafloor. To do so, scientists measure silicon **isotopes**, which is a powerful way to understand what diatoms were doing in the past, as well as what the conditions were like for these diatoms.

VESICLE

A structure inside a cell, consisting of liquid enclosed by an additional membrane. Vesicles transport and store material within the cell.

ISOTOPES

Atoms of the same element with the same number of protons but a different number of neutrons and, thus, a different mass number.

DID YOU SAY ISOTOPE?

Atoms are the main building blocks of every existing thing. Atoms are made of small parts called protons, electrons, and neutrons (Figure 2). An atom is identified by the number of protons it contains. For example, a silicon atom contains 14 protons. In most cases, an atom contains the same number of neutrons as protons, meaning 14 neutrons for silicon. The number of protons plus the number of neutrons gives the **mass number** of the atom. For example, most silicon atoms have a mass number of 28. However, in rare cases, silicon can have 16 neutrons instead of 14, so its mass number will be 30 instead of 28. These little variations in the number of neutrons produce "light" atoms of silicon (with a mass number of 28) and "heavy" atoms of silicon (with a mass number of 30). Those lighter and heavier atoms of silicon are called isotopes. In nature, the most abundant silicon isotope has a mass number of 28 and is called ^{28}Si, and the least abundant has a mass number of 30 and is called ^{30}Si.

MASS NUMBER

The number of protons plus the number of neutrons of an atom.

WHY DO DIATOMS CARE ABOUT SILICON ISOTOPES?

Diatoms prefer to use the lightest silicon isotope (^{28}Si) when they build their skeletons. In scientific terms, they **fractionate** silicon isotopes, which means they preferentially take up the lighter isotope (^{28}Si) to a certain amount [3]. This might sound complicated, but here is an example that might help you understand.

FRACTIONATION

The preferred ratio of two isotopes that are taken up during a specific process.

Figure 2

An atom contains protons and neutrons in its nucleus and electrons spinning around them. The number of protons defines the element. The sum of neutrons and protons gives the mass number of the element. The number of neutrons can change, which does not change the type of element but does change its mass number. An atom of silicon has 14 protons (pink circles) and can have 14 or 16 neutrons (blue circles), changing the mass number from 28 to 30. Atoms of elements with different numbers of neutrons are called isotopes. Here you can see the isotopes ^{28}Si and ^{30}Si.

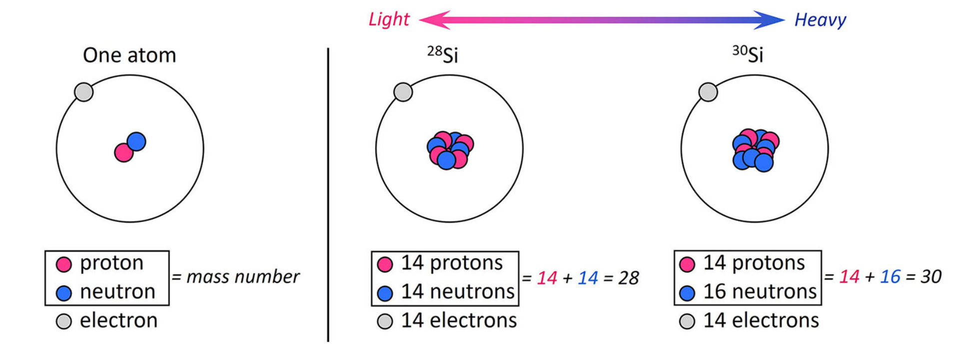


Figure 2

Diatoms are just like you and me: they prefer certain foods. Imagine having a bag full of pink and blue jellybeans in equal proportions. You like both, but you have a small preference for pink jellybeans. Because you are wise, you decide not to eat the whole bag at once, but to eat only a small fraction of jellybeans daily. On the first day, you obviously grab more pink jellybeans than blue ones because pink is your favorite. The second day, you do the same thing, but you notice that there are now more blue than pink jellybeans in your bag. On the last day, it is difficult to find pink jellybeans in your bag, and you end up with more blue jellybeans than pink in your hand. By preferentially eating pink jellybeans, you changed the ratio of jellybeans colors in your bag and your hand. You have increased the ratio of blue jellybeans (your less favorite) in the bag and your hand.

Diatoms do the same thing with silicon isotopes in the ocean (Figure 3). They prefer to use the ^{28}Si isotope so, as they continue to take up their favorite silicon isotope from the water, they increase the ratio of ^{30}Si that remains in the water. This means that the diatoms that grow after them will have to form opal with more ^{30}Si [4].

RECONSTRUCTING THE PAST WITH THE SILICA-PRINT

Because of fractionation, diatom activity leaves an imprint (or silicon-print) in both seawater and in their opal skeletons. If diatoms take up a lot of silicon, they will eventually have to incorporate more ^{30}Si into their skeletons because that is the isotope left over after they use up their favorite, ^{28}Si. On the other hand, when diatoms take up less silicon, they will use less ^{30}Si. When diatoms die, they sink to the seafloor where they are buried, saving this silicon-print. By measuring the proportion of the two silicon isotopes in these old diatom skeletons from the seafloor, paleoceanographers can investigate diatoms' activity in the surface water in the past.

To do this, paleoceanographers use ships equipped with devices that collect seawater from the ocean surface and diatoms from the seafloor. Then, scientists remove the silicon from the seawater and

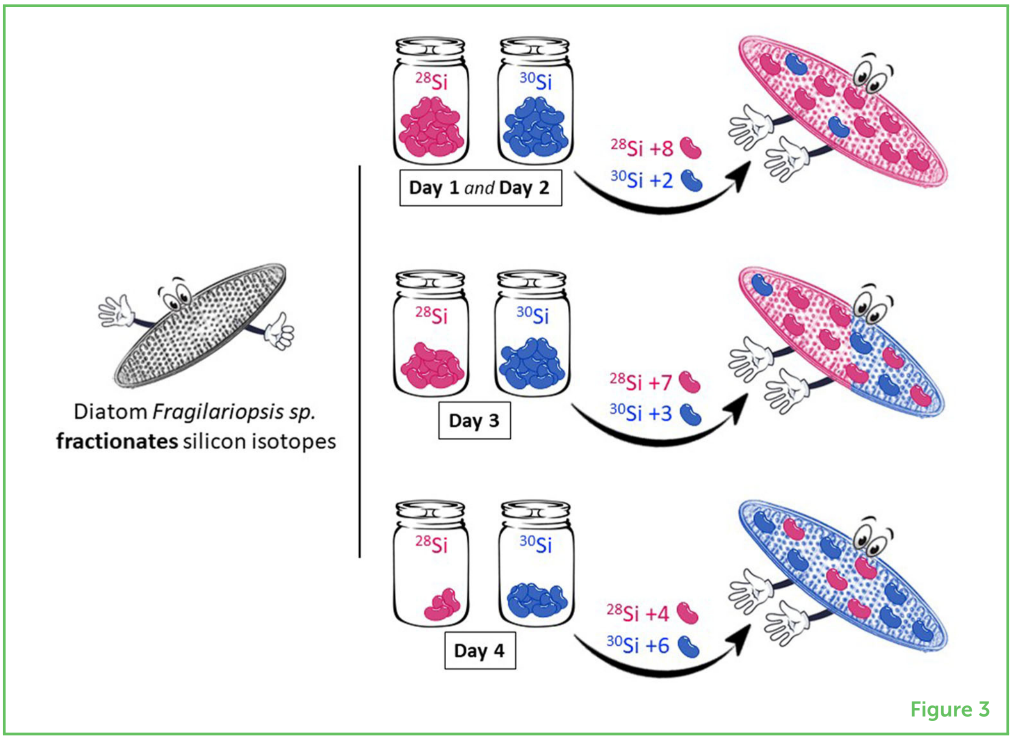


Figure 3

Diatoms of the species *Fragilariopsis sp.* fractionate (or favor) the lightest isotope (^{28}Si, pink jellybeans). By choosing more ^{28}Si compared to the heavier isotope ^{30}Si (blue jellybeans), the diatoms change the proportion of silicon isotopes available in seawater (the jars) and within their skeletons. With time, both the seawater and the diatoms become enriched in ^{30}Si because most of the ^{28}Si has been used up.

the diatoms' skeletons in their laboratories and use instruments that measure the ratio between the two silicon isotopes. We call this ratio δ^{30}Si (pronounced "delta-30-silica"). When δ^{30}Si is high, there is more ^{30}Si in the sample, and when δ^{30}Si is low, there is more ^{28}Si in the sample [4, 5].

By measuring δ^{30}Si in the seawater, scientists can calculate the amount of silicon that diatoms have taken up in the last week or the last month. When measuring δ^{30}Si in the diatoms preserved on the seafloor, paleoceanographers can investigate how much silicon was used by diatoms that lived in the ocean thousands of years ago. Therefore, scientists can find out how abundant and healthy diatoms were and if they could absorb a lot of CO_2 from the atmosphere by photosynthesis in the past.

DO WE KNOW EVERYTHING ABOUT DIATOMS' SILICON ISOTOPE EATING HABITS?

The investigation of silicon-prints by measuring silicon isotopes in diatoms' skeletons works very well. But scientists still have many questions regarding the fractionation of silicon isotopes by diatoms. For example, we assume that diatoms always use the two silicon isotopes in the same ratio. That means the proportion of ^{30}Si to ^{28}Si they take up does not change. To use the jellybeans example, this is like assuming you always take the same proportion of pink and blue jellybeans. Today, we are starting to think that this ratio can change, but we still do not know why. Maybe different types of diatoms have different preferences and fractionate silicon isotopes differently. Diatoms might also change the ratio of the two silicon isotopes they normally use depending on surrounding conditions, such as the availability of other nutrients and light. These important questions need to be answered because we use silicon isotopes to reconstruct how diatoms influence ocean chemistry and how they have interacted with the climate in the past. We need to fully understand how things work in modern times to accurately evaluate what happened in the past.

Despite all the unknowns that still need to be explored, silicon isotopes are a powerful tool that helps us to track the activity of diatoms in the past and in today's oceans, and to better understand the role of the ocean in the regulation of Earth's climate. Eventually, this information will allow researchers to better predict how the environment will respond to climate change and how the consequences of human activities affect the health of ocean ecosystems.

ACKNOWLEDGMENTS

This manuscript is part of a series of 6 manuscripts about the marine silicon cycle by the Early Career Researchers SILICAMICS group. We thank the SILICAMICS ECRs consortium for its enthusiasm for putting this project together. We warmly thank the four young reviewers and their mentors for their sensible comments that greatly improved this manuscript. This work was supported by grants from the National Science Foundation #OCE-2048998 (IC).

REFERENCES

1. Tréguer, P., Bowler, C., Moriceau, B., Dutkiewicz, S., Gehlen, M., Aumont, O., et al. 2018. Influence of diatom diversity on the ocean biological carbon pump. *Nat. Geosci*. 11:27-37. doi: 10.1038/s41561-017-0028-x
2. Martin-Jézéquel, V., Hildebrand, M., and Brzezinski, M. A. 2000. Silicon metabolism in diatoms: implications for growth. *J. Phycol*. 36:821-40. doi: 10.1046/j.1529-8817.2000.00019.x
3. Fry, B. 2006. Stable Isotope Ecology. New York, NY: Springer.
4. De La Rocha, C. L., Brzezinski, M. A., and DeNiro, M. J. 1997. Fractionation of silicon isotopes by marine diatoms during biogenic silica formation. *Geochimica et Cosmochimica Acta*. 61:5051-6. doi: 10.1016/S0016-7037(97)00300-1
5. De La Rocha, C. L., Brzezinski, M. A., DeNiro, M. J., and Shemesh, A. 1998. Silicon-isotope composition of diatoms as an indicator of past oceanic change. *Nature* 395:680-3. doi: 10.1038/27174

SUBMITTED: 28 February 2023; **ACCEPTED:** 23 November 2023;
PUBLISHED ONLINE: 14 December 2023.

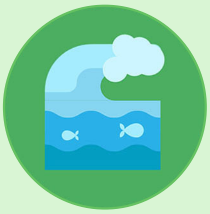
EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Karen Holmberg and Catherine A. Walsh

CITATION: Closset I, Doering K and Liguori BTP (2023) Diatoms Like It Light! How Diatom Eating Habits Help Us Understand the Past Ocean. Front. Young Minds 11:1176653. doi: 10.3389/frym.2023.1176653

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



HELENA, MOMO, TATI , AGES: 11–12
This fun-loving trio enjoys science and writing. They love to explore new topics and are especially interested in eco-friendly ways to combat climate crises to create a brighter future for our planet. Helena likes to hike and play soccer. She also adores her three cats. Momo enjoys being in nature, especially in city parks, because urban ecology shows her how strong nature can be. She is growing all sorts of plants in her hydroponic garden inside her city apartment. Tati loves dogs. She is an amazing sewer and builder.

JUDE, AGE: 15
I am a big fan of both dogs and cats, I have trained my cat to walk on a lead so we can go for walks together in my spare time. I also love music and spend a lot of time playing my guitar. I enjoy reading about biochemistry (especially plant related) and one day would like to study the subject at university.

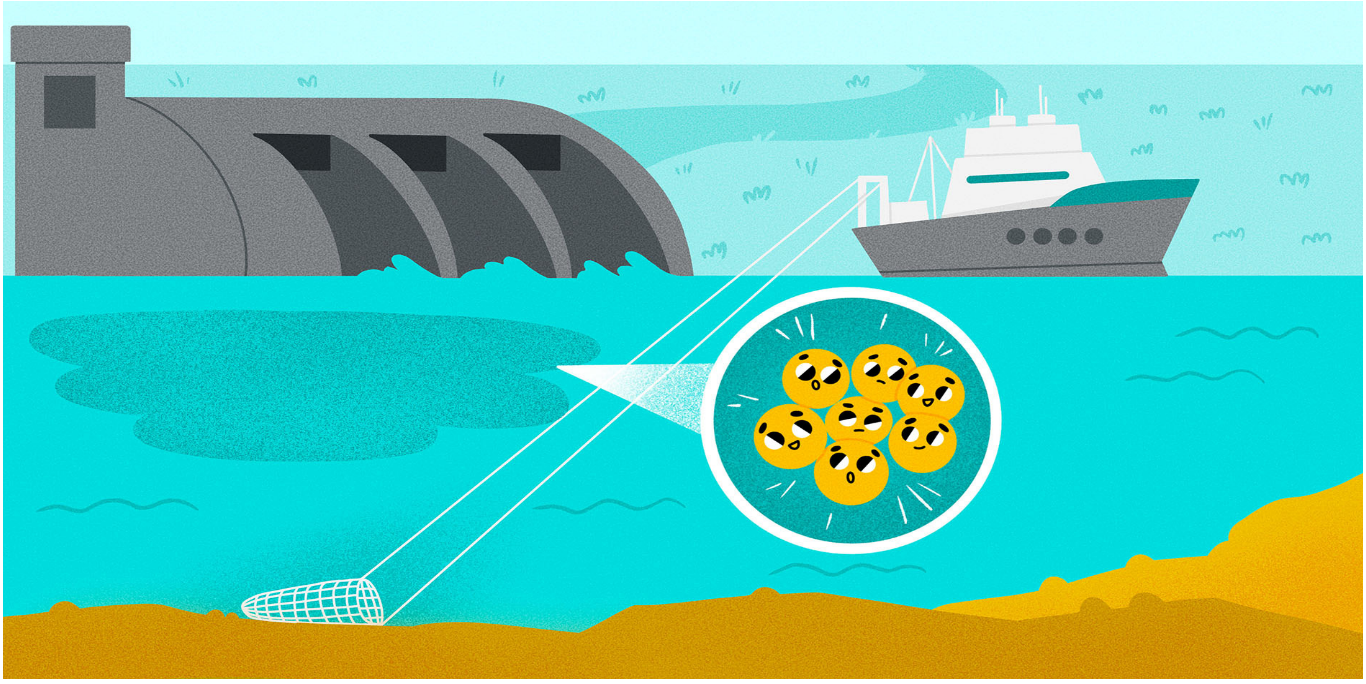
AUTHORS

IVIA CLOSSET
I am a marine biogeochemist and have always been obsessed with the mysteries of the unseen and wildest part of the ocean. Science has quickly become a way for me to experience and understand the balance of the world around us. I use stable isotopes to track modern and past ocean processes, such as phytoplankton activity, with a strong focus on the silicon cycle and the Southern Ocean. I am working using various types of samples, from seawater, delicate diatoms, frozen sea ice, and muddy sediments from the deep seabed. *ivia@ucsb.edu

KRISTIN DOERING
I am a marine biogeochemist and micropalaeontologist. I work on discovering how the ocean's nutrient cycle has changed in the past. To do so, I look at different microfossils, such as diatoms, radiolarians, and sponge spicules. The chemical properties of these organisms compared to today's seawater tell me how much nutrients there were in the past ocean and how much of it was used. I am fascinated by studying microfossils as they can tell us so much about the past, and I am constantly working to improve our understanding of them. *kristin.doering@geol.lu.se

BIANCA T. P. LIGUORI
My research focuses on the biogeochemical silicon (Si) cycle using stable Si isotopes as a tool. The stable Si isotope composition of different reservoirs like seawater, porewater or diatoms bears information on the dominant pathways and processes by which Si is transported to and cycled in the ocean. Therefore, understanding these factors is of vital importance for our general understanding of the global Si cycle. For that, I work with seawater, particulate, marine pore waters and sediment samples from the Arctic and Pacific Oceans.

EARTH SCIENCES
Published: 12 December 2023
doi: 10.3389/frym.2023.1176391



HOW HUMAN ACTIVITIES ARE DISRUPTING THE SILICON CYCLE

Zhouling Zhang [1*] ***and María López-Acosta*** [2*]

[1] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany*
[2] *Department of Oceanography, Instituto de Investigaciones Marinas (IIM), CSIC, Vigo, Spain*

YOUNG REVIEWERS:

MOMO
AGE: 11

YUHENDRA
AGE: 13

Dissolved silicon is an essential nutrient for the growth of various ocean organisms that need it to build their skeletons. Most of the dissolved silicon that sustains these organisms comes from the breakdown of silicon-containing rocks on land. In recent decades, human activities have greatly disturbed the transport of silicon from land to ocean. For example, dams built to generate electricity can interrupt the transport of dissolved silicon and starve downstream areas. Fertilizers and other human pollution add large amounts of non-silicon nutrients to rivers, lakes, and reservoirs, which can stimulate organisms to grow and use up silicon before it reaches the ocean. In addition, consequences of climate change can also impact the silicon cycle. In this article, we explain how human activities have disturbed the silicon cycle and discuss how climate change may affect it in the future.

WHY DO WE CARE ABOUT SILICON?

Diatoms are tiny single-celled algae that play an important role in regulating Earth's climate. They take in carbon dioxide (CO_2) and use it, along with the sun's energy, to produce sugars to feed themselves, via the process of photosynthesis. When diatoms die, they sink to the bottom of the ocean, removing CO_2 from the atmosphere and storing it in the ocean. Since CO_2 is an important greenhouse gas, changes in the numbers of diatoms can therefore have a significant impact on Earth's climate. The nutrient that diatoms need the most is silicon, which they need to build up their shells. There are other organisms that need silicon to form their siliceous (glassy) skeletons, such as rhizarians and sponges. Together, organisms that use silicon to build their skeletons are called **silicifiers**. To learn more about silicifiers, see this Frontiers for Young Minds article. The growth of silicifiers depends on the availability of dissolved silicon in the surrounding water. Therefore, silicon is crucial for silicifiers and the health of aquatic ecosystems [1].

SILICIFIERS

Organisms that use dissolved silicon from their environments to build their skeletons made of glass. Some examples are diatoms, rhizarians, and sponges.

Silicon in ocean water comes from the breakdown and **weathering** of rocks on land. It is then transported to the ocean by various waterways. Before it arrives at the ocean, silicon travels through rivers, lakes, and reservoirs, where it is consumed by silicifiers or incorporated into clay minerals. All these processes move silicon around and change it creating a cycle that we call the silicon cycle. The amount of silicon that is delivered to the ocean is often in excess compared to other nutrients essential for the growth of silicifiers, such as nitrogen and phosphorus. So, in the past, the availability of dissolved silicon was never a concern, especially near the coasts. However, in the past few decades, human activities have changed this status, disturbing the transport of silicon from land to ocean and thus its availability in coastal seas (Figure 1).

WEATHERING

The process by which rocks, soil, and other materials are broken down and worn away by the effects of wind, water, and other natural forces over time.

DAMMING AND EUTROPHICATION

Hydropower technologies, such as **damming**, can interrupt the transport of silicon to the ocean (Figure 1). Dams are structures built to hold back flowing water in rivers and raise its level to form a reservoir. Dams are used for a variety of purposes, like generating electricity and controlling river flow. Europe and the United States started the first boom in hydropower development at the end of the 19th century, while other countries, such as China, Brazil, and India, boosted a second boom in the 21st century. Damming changes the way river water and sediment flow. As water flows through the dam, it slows down and sediment particles settle out, accumulating at the bottom of the reservoir. Over time, this sediment accumulates upstream of the dam, forming a thick layer of material that may include a lot of silicon. Dams also impact the transport of silicon by altering the flow and velocity of the water. By slowing the water down, dams increase

DAMMING

The construction of a barrier, typically a concrete wall, across a river to control the flow of water, often for flood control, hydropower generation or water storage purposes.

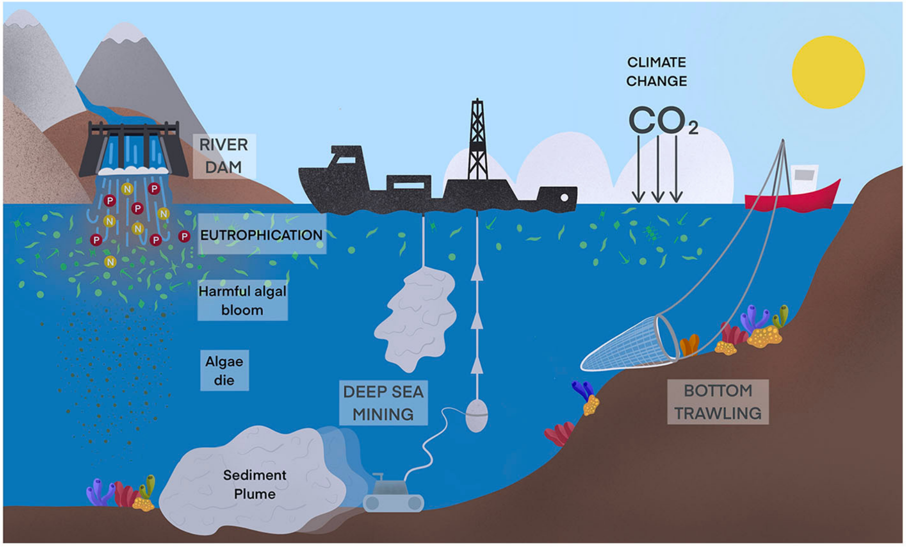


Figure 1

Figure 1

Human activities can disturb silicifiers and the silicon cycle in the ocean. Some activities, such as bottom trawling and deep-sea mining, can negatively affect bottom-dwelling silicifiers and movement of silicon from the sediments into the deep ocean waters. This can form a sediment plume, which is like a cloud of dirt or mud occurring when sediments get stirred up and float around in the water, negatively affecting organisms living on the seabed. Other human activities that can lead to a decrease of silicon in seawater include ocean acidification due to climate change, river dams, and eutrophication. N and P represent excess nitrogen and phosphorus causing eutrophication.

EUTROPHICATION

Eutrophication is the nutrient over-enrichment of water, primarily nitrogen and phosphorus, causing excessive growth of algae and other aquatic plants and altering the water quality and the ecosystem.

HARMFUL ALGAL BLOOM

Rapid and excessive proliferation of certain algal species in aquatic environments, often resulting in the production of toxins that can have detrimental effects on ecosystems, marine life and human health.

the time water stays in the reservoir, which stimulates diatom growth there. This can result in more silicon remaining in the reservoir and never making it to the ocean. Globally, dams retain 5.3% of the active silicon loaded into rivers by rock weathering [2].

Eutrophication, which is when a body of water receives an excessive amount of nutrients like nitrogen and phosphorus, also alters the transport of silicon to the ocean. Farming, factories, and people living in cities release a lot of nitrogen and phosphorus into rivers, lakes, and reservoirs. The increased nutrients can cause an overgrowth of algae in those waters and use up a lot of the available silicon in the water, preventing it from reaching the ocean. The combination of inland eutrophication and damming decrease the total global movement of dissolved silicon to the ocean by nearly 30% [3].

Eutrophication also takes place in the ocean close to the coasts, increasing the numbers of diatoms in coastal regions. When those diatoms die, their skeletons sink to the bottom in those coastal regions, which further reduces the amount of dissolved silicon in other areas of the ocean. The overall reduction in dissolved silicon may have harmful effects on the entire ocean food chain, because diatoms are a vital link in this chain. When there is not enough dissolved silicon for diatoms to grow, these conditions often trigger blooms of other organisms that do not require silicon, some of which can produce toxic substances. These are called **harmful algal blooms** and they can have significant impacts on the ecosystem and human health [3].

The Baltic Sea is a good example of the impact of damming and eutrophication on silicon balance. Delivery of silicon to the Baltic Sea is greatly reduced by inland eutrophication and damming. The recycling of silicon within the Baltic Sea is also altered by eutrophication [4].

This is because increased nitrogen and phosphorus entering the Baltic Sea, along with decreased amounts of silicon, lead to widespread eutrophication, which further decreases the dissolved silicon in the ocean water. Regular monitoring has shown a decrease in dissolved silicon in the surface water of the Baltic Sea from the 1970s to the end of the 20th century (Figure 2). The decreasing availability of silicon and the resulting harmful algal blooms have made the water unsafe for swimming or other recreational activities.

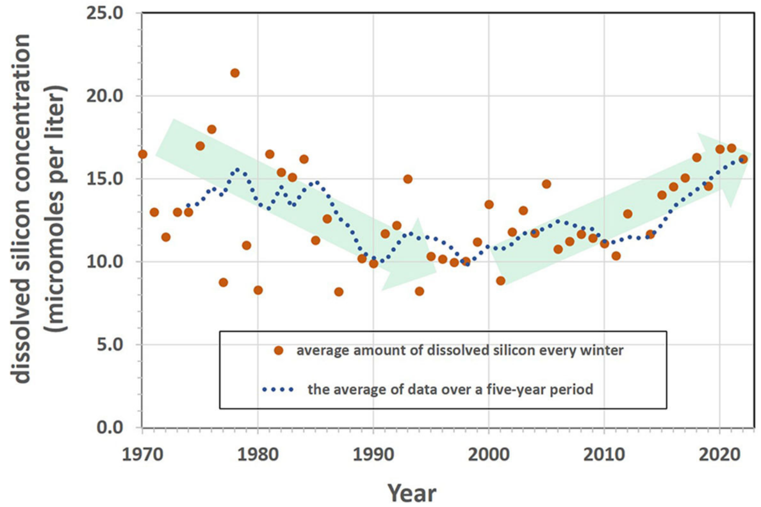


Figure 2

Figure 2

From the 1970s until today, the amount of dissolved silicon has changed over time in the surface water of the central Baltic Sea. The green arrows indicate the decreasing and increasing trends of dissolved silicon. Starting in 1970, the Baltic Sea experienced a reduction of the amount of dissolved silicon due to the construction of dams and the eutrophication affecting rivers flowing into this sea. More recently, levels are increasing because the neighboring countries are working to reduce the effect of water retention in dams and the water pollution entering the Baltic Sea. Data used to create this plot come from https://sharkweb.smhi.se/hamta-data/.

SEABED IMPACTS AND CLIMATE CHANGE

Other human activities that involve the ocean floor can also impact the silicon cycle—as well as the living things that call the seabed their home. **Bottom trawling**, which involves dragging heavy nets along the ocean floor to catch fish, and **deep-sea mining**, which involves digging up valuable minerals from the seabed, are harmful to the ocean floor and its creatures. These creatures include siliceous organisms such as sponges, and also tiny animals that live within the sediment that help transport dissolved silicon from the sediment back into to the water. Without these organisms, the movement of dissolved silicon into the deep ocean waters will decrease and silicon cycling on the seabed will be less active [5].

To add fuel to the fire, human-induced climate change also affects the silicon cycle in the ocean. To learn more about climate change, see this Frontiers for Young Minds Collection. For example, the increasing CO_2 in the atmosphere, mainly due to burning fossil fuels, causes the ocean to absorb more and more CO_2. The CO_2 changes the properties of ocean water, making it more acidic. This process is known as **ocean acidification**, and it can alter the silicon cycle and impact the growth of silicifiers. Scientists have recently discovered that

BOTTOM TRAWLING

A fishing method in which a large net, often weighted, is dragged along the ocean floor to capture fish and other marine organisms living near the seabed.

DEEP-SEA MINING

Industrial activity to extract valuable minerals and resources from the seabed at great depths.

OCEAN ACIDIFICATION

A consequence of climate change, which occurs as the ocean absorbs carbon dioxide, leading to increased acidity and harming marine organisms and ecosystems.

ocean acidification might lead to a decline in diatoms in the future [6]. When diatoms die, their shells sink into the deep ocean, where they dissolve and release silicon back into the water. This regenerated silicon moves back into the sunlit surface water due to ocean currents and mixing processes. Other diatoms then use the regenerated silicon to build their shells. However, as a result of ocean acidification, the shells of diatoms dissolve more slowly, which ultimately reduces the amount of silicon returning to the sunlit surface water. Therefore, scientists predict that ocean acidification will eventually decrease the number of diatoms in the ocean. In the future, the world will experience changes in temperature, rain, plants, and ocean currents due to climate change. Unfortunately, we still do not know exactly how these changes will eventually affect the amount of silicon and the functioning of marine ecosystems.

ACTION CAN RESTORE THE BALANCE

Human activities affect the cycling of essential nutrients such as silicon. The effects often occur far from where the human activity takes place, as happens in coastal ecosystems, for example, after a dam is built upstream. It is difficult to predict the future status of the silicon cycle. However, scientists believe that ongoing changes to the silicon cycle due to human activities and climate change will certainly harm aquatic ecosystems. It is therefore important that scientists and governments study and monitor the silicon cycle, to understand the effects of human activities and climate change and to take appropriate actions to reduce human impacts. Near the Baltic Sea, neighboring countries are working together to reduce the amount of pollution entering the water. These efforts are making a difference—we can see that the Baltic Sea ecosystem is starting to get better. The amount of silicon in the surface water in winter is even getting back to the levels seen at the beginning of the 21st century (Figure 2). This shows that we really *can* make positive changes if we take action!

Young people can make significant contributions to addressing environmental problems. They can support sustainable water management by advocating for responsible dam construction and promoting alternatives, like low-impact hydropower. They can also practice ecofriendly habits such as conserving water, using sustainable products, and saving energy. Supporting organic farming and otherwise helping to reduce the use of chemical fertilizers can help too. By spreading awareness, joining environmental clubs, and participating in community clean-up activities, young people can protect the environment and help restore balance to the silicon cycle.

ACKNOWLEDGMENTS

This article is part of a series of six manuscripts about the marine silicon cycle put together by the ECR SILICAMICS group. We thank the SILICAMICS ECRs consortium for its enthusiasm for putting this project together. We also thank Natalia Llopis Monferrer for her work on Figure 1. ZZ received funding from the *Bundesministerium für Bildung und Forschung* (project SO289 - S Pacific GEOTRACES) and ML-A received funding from the *Xunta de Galicia* for her postdoctoral fellowship (IN606B-2019/002, ARISE) and grant (IN606C-2023/001, SPICA).

REFERENCES

1. Garnier, J., Beusen, A., Thieu, V., Billen, G., and Bouwman, L. 2010. N:P:Si nutrient export ratios and ecological consequences in coastal seas evaluated by the ICEP approach. *Global Biogeochem. Cycles* 24:1–12. doi: 10.1029/2009GB003583
2. Maavara, T., Dürr, H. H., and Van Cappellen, P. 2014. Worldwide retention of nutrient silicon by river damming: From sparse data set to global estimate. *Global Biogeochem. Cycles* 28:842–855. doi: 10.1002/2014GB004875
3. De La Rocha, C., and Conley, D. J. 2017. *Silica Stories*. Cham: Springer International Publishing.
4. Zhang, Z., Sun, X., Dai, M., Cao, Z., Fontorbe, G., and Conley, D. J. 2020. Impact of human disturbance on the biogeochemical silicon cycle in a coastal sea revealed by silicon isotopes. *Limnol. Oceanogr.* 65:515–528. doi: 10.1002/lno.11320
5. Olsgard, F., Schaanning, M. T., Widdicombe, S., Kendall, M. A., and Austen, M. C. 2008. Effects of bottom trawling on ecosystem functioning. *J. Exp. Mar. Biol. Ecol.* 366:123–133. doi: 10.1016/j.jembe.2008.07.036
6. Taucher, J., Bach, L. T., Prowe, A. E. F., Boxhammer, T., Kvale, K., and Riebesell, U. Enhanced silica export in a future ocean triggers global diatom decline. *Nature* (2022) 605:696–700. doi: 10.1038/s41586-022-04687-0

SUBMITTED: 28 February 2023; **ACCEPTED:** 23 November 2023;
PUBLISHED ONLINE: 12 December 2023.

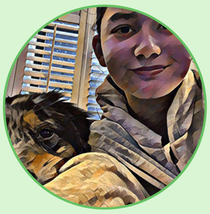
EDITOR: Emily King, Xiamen University, China

SCIENCE MENTORS: Ramesh T. Subramaniam and Karen Holmberg

CITATION: Zhang Z and López-Acosta M (2023) How Human Activities Are Disrupting the Silicon Cycle. Front. Young Minds 11:1176391. doi: 10.3389/frym.2023.1176391

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



MOMO, AGE: 11

Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she is at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

YUHENDRA, AGE: 13

Hi! It is great to be a reviewer. I am 13 years old and I like Science and Maths. They are my favorite subjects at school. As a past time I do Lego read books and spend time with my family. I also like to play video games.

AUTHORS

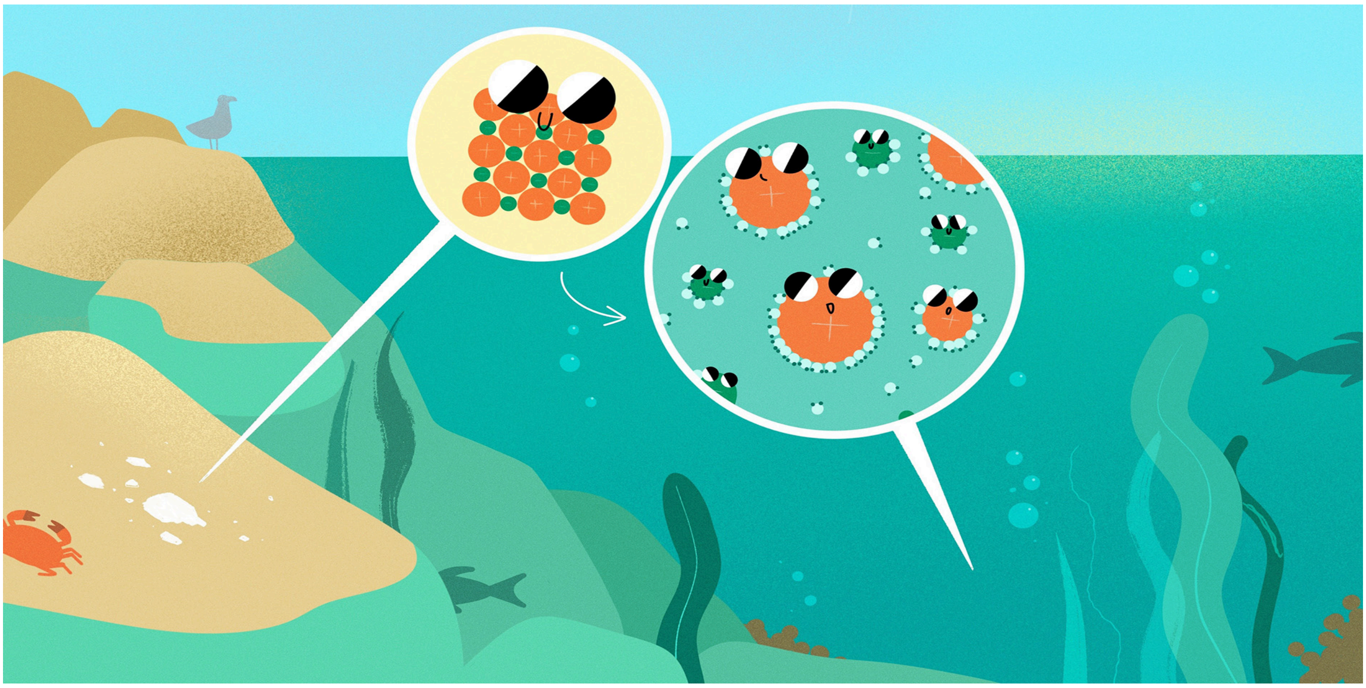
ZHOULING ZHANG

As a marine chemist, my research focuses on (bio)geochemical cycling and ocean circulation. I am curious about the sources of ocean essential elements, such as from rivers, sediments, hot hydrothermal vents, etc. My aim is to figure out how these elements change in the ocean because of (bio)geochemical processes. I have explored lots of different parts of the ocean from estuaries to the open ocean, like the Amazon estuary, the Congo shelf, the Baltic Sea, the South China Sea, and the South Pacific Ocean. *zzhang@geomar.de

MARÍA LÓPEZ-ACOSTA

I am a marine ecologist interested in the role of bottom-dwelling organisms in ocean nutrient cycling, with a special interest in silicon. My model organisms are sponges, which I have been studying for more than a decade and still find as fascinating as the first day. I have studied sponges in the shallow waters of the North Atlantic Ocean and Mediterranean Sea by diving, and in the deep waters of the Norwegian Sea, Barents Sea, and North Atlantic Ocean using underwater robots. I am now studying the effects of human impacts on silicon recycling in sponges and other silicifying benthic organisms. *lopezacosta@iim.csic.es

EARTH SCIENCES
Published: 11 December 2023
doi: 10.3389/frym.2023.1097831



WHY IS THE SEA SALTY AND DOES IT MATTER?

Colin A. Stedmon and André W. Visser*

National Institute of Aquatic Resources, Technical University of Denmark, Kongens Lyngby, Denmark

YOUNG REVIEWERS:

PRICE
AGE: 14

SEBASTIAN
AGE: 14

A mouthful of water while swimming in a lake is unpleasant but nothing compared to the same situation during a swim in the ocean. A sudden mouthful seawater leaves you gasping for a glass of water to wash the salty taste from your mouth. But have you ever stopped to consider why the sea is salty? In this article, we will dive into the realm of ocean salinity (salt concentration) and show that there is more to it than you may have thought. Where does the ocean's salt come from? What is it made of and how is salinity measured? Finally, why should the saltiness of the ocean interest us at all?

WHAT IS SALT?

Salt is more than just the white crystals in the shaker at the dinner table that we add to food to make it tastier. Let us dig a little deeper. In the ocean, 97% of the salt is made up of **ions** (electrically charged atoms or molecules) such as sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}) and magnesium (Mg^{2+}) (Figure 1).

The ocean receives most of its salt from a process called chemical rock weathering (Figure 2A). The combination of water from rain,

ION

An atom or molecule that has a charge because it has gained or lost electrons. Positively charged ions (Na^+) are called cations; negatively charged ions (Cl^-) are called anions.

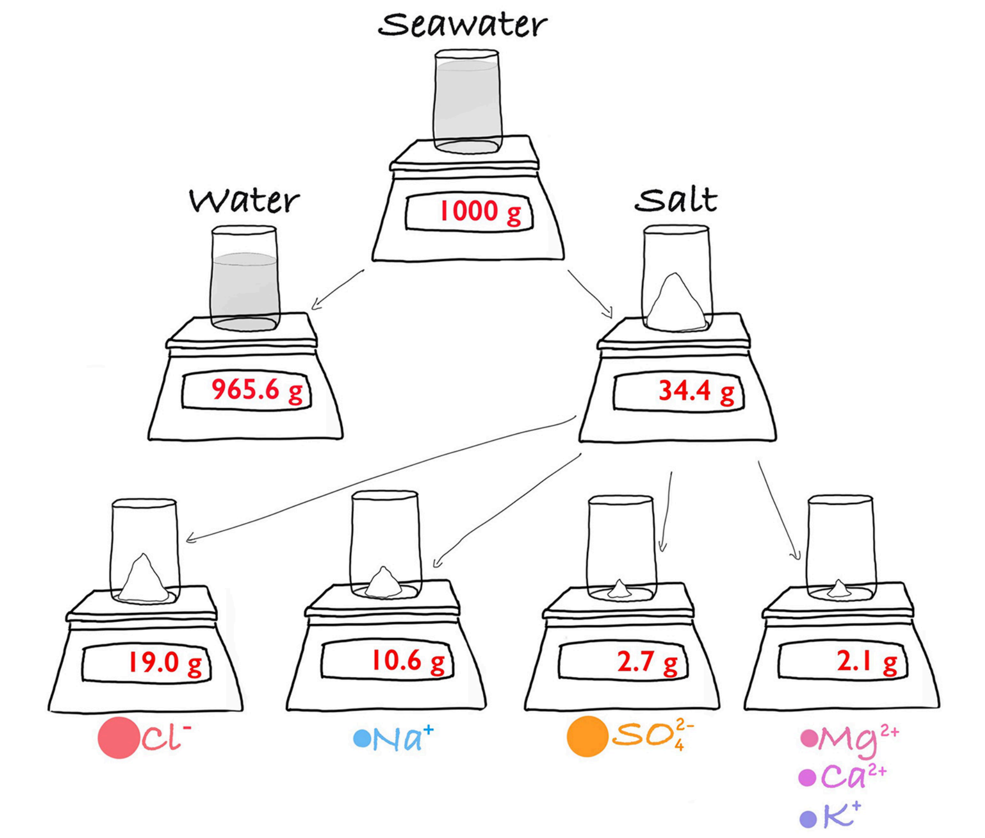


Figure 1

Figure 1

What is in a kilo (1,000 g) of seawater? Most of it is water (956.6 g). The remainder (just over 34 g) consists of a collection of salts. Chloride (Cl^-) and sodium (Na^+) are the dominant salts, representing 86% of the total. Much of the remaining salt is sulfate (SO_4^{2-}), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), and potassium (K^+).

plus oxygen (O_2) and carbon dioxide (CO_2) from the air, acts to react with and **dissolve** the minerals that rocks are made of. You can see this process in places where rainwater has smoothed rock surfaces, or on statues or stone building decorations that have lost their original shapes.

Water molecules consist of hydrogen and oxygen atoms. The hydrogen end of the water molecule has a slight positive charge, and the oxygen end has a slight negative charge. This makes water an excellent **solvent**, which means a substance that can dissolve ions. Rocks and minerals contain a mixture of ions, which can be grouped into those with a negative charge (anions) and those with a positive charge (cations). Since opposite charges attract, water molecules surround the ions and isolate them from each other (Figure 2A). So, although river water does not taste salty, it actually does contain salt—just a very low **concentration**.

WHY IS SEAWATER SALTY?

Rivers ultimately flow out to the sea, taking the dissolved salts from rock weathering with them (Figure 2B). When ocean water **evaporates** into the air, the salts are left behind. The evaporated water eventually

DISSOLVE

When individual molecules of a substance become surrounded by molecules of a liquid, such as salt ions in water.

SOLVENT

A liquid that can dissolve a solid or gas. Water is an excellent solvent.

CONCENTRATION

The amount of a substance in a volume of liquid or gas; e.g., 34 g of salt in 1 L of water has a salt concentration of 34 g/L.

EVAPORATION

When water molecules are warmed up enough that they can move further away from each other, turning a liquid into a gas.

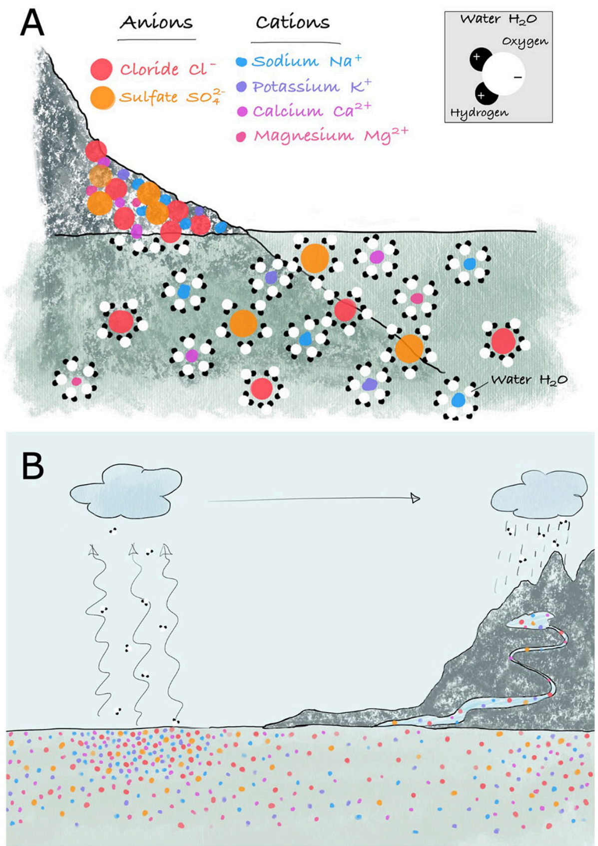


Figure 2

Figure 2

(A) Rocks are made of a mixture of anions and cations. Water molecules have a weak positive charge at one end and a weak negative charge at the other. Water molecules can surround rock ions, with opposite charges attracting, and isolating the ions from each other. This dissolves the rock, in a process called chemical rock weathering. **(B)** Salts are eventually carried to the ocean. Ocean salinity is highest in the open ocean, where water is lost to evaporation and the dissolved salts are left behind. Rivers have low salinities, and coastal waters are generally in between.

falls as rain (or snow) over land. This process repeats and supplies more salt to the sea.

But this must only be part of the story, otherwise the oceans would be gradually increasing in **salinity**, eventually becoming so salty that they could not dissolve any more salt. Seawater is salty, but not that salty! Try experimenting yourself: see how much table salt you can dissolve in 1 L of water. It will be much more than the ∼35 g/L there is in the ocean. So, there must be other processes at play that slowly remove salt from the ocean. Oceanographers call these processes a salt "sink," just as your kitchen sink removes water that comes from the tap.

SALINITY

Salt concentration; a measure of how salty seawater is.

Salt is slowly removed from the ocean by several processes. Evaporation of water in shallow coastal lagoons can cause the salt concentrations to increase so much that it **precipitates** and collects on the seafloor. This is how sea salt can be harvested for use in our food. Sea spray can also slowly move salt from the ocean to land. The water in the spray evaporates and leaves the salt behind on land. Finally, saltwater seeping through cracks in the ocean floor near undersea volcanic ridges also slowly remove salt from the ocean. But, on the whole, salt ions linger in the ocean thousands of times longer (several

PRECIPITATE

When liquid molecules (such as water) can no longer keep molecules of a substance separate from each other and the substance becomes solid (e.g., salt crystals).

million years) than water molecules do (thousands of years), making seawater saltier than river water.

MEASURING SALINITY

DENSITY

The mass of a specific volume of gas, liquid or solid. The density of seawater is influenced by water, its temperature and the concentration of substances dissolved in it.

Worldwide, millions of measurements of ocean salinity are made every day. Let us look at why this is necessary and how it is done. The salinity and temperature of seawater influences the **density** of seawater. The more salt that is dissolved in water, the denser it is: while 1 L of freshwater at 10°C weighs 1,000 g, 1 L of seawater at the same temperature weighs 1,026 g. Differences in ocean temperature and salinity between depths and locations influence ocean currents (to learn more about this, read this Frontiers for Young Minds article). If we want to understand how the oceans affect local weather, global climate, and the distribution of resources such as fish, we need to understand ocean circulation, and for that salinity plays a role.

Measuring salinity is no easy task. As mentioned earlier, salt is not one substance but a mixture. In the early days of ocean exploration, precise volumes of seawater were evaporated and the salts left behind were weighed. In the 1800s, the Danish geologist Forchhammer went further and determined the concentrations of individual salts [1], which is a very time-consuming process even for just one water sample. After carefully measuring samples sent by explorers from all over the world, Forchhammer discovered that the relative amounts of the various salts in ocean water was almost always the same, which made things much simpler. This meant that scientists could measure just one salt, such as the chloride ion (Cl^-), which is present in high concentrations and is easy to measure. Salinity can then be calculated by multiplying by the constant Forchhammer derived: 1.812. This number is remarkably similar to modern estimates (1.815) [2], which is amazing given that he worked with simple equipment and did not even have electric lighting!

In the 1960s, electronic equipment was developed to assess salinity by measuring how well a seawater sample conducts electricity. This is the basis of modern salinity-measuring devices, which can be mounted on drones called Argo floats that are released into the ocean and send data back via satellites (to read more about these, see this Frontiers for Young Minds article). These underwater drones have a collection of sensors that can measure pressure (for depth), temperature, and conductivity (for salinity). They drift with ocean currents and can automatically control how well they float. When they sink and rise, they collect measurements of seawater properties that enable scientists to construct maps of ocean salinity (Figure 3).

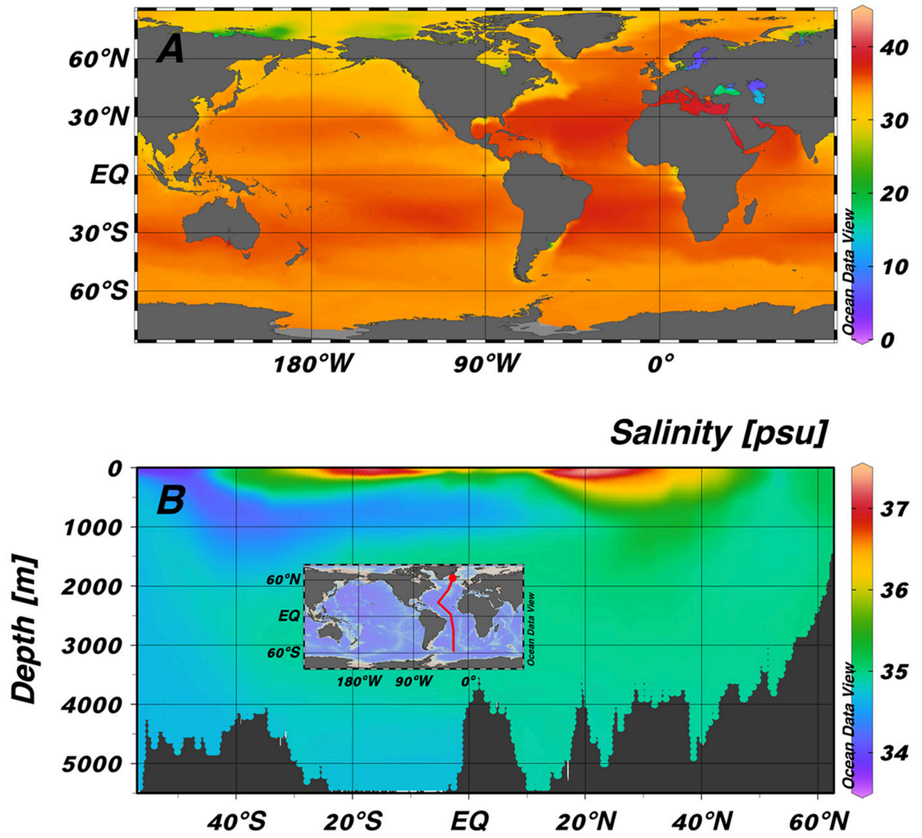


Figure 3

Figure 3

(A) The salinity of the surface ocean around the world. Dark red colors show the highest salinity, which is often in the tropics where hot weather leads to more evaporation. **(B)** A slice through the Atlantic Ocean (red line on map), showing how salinity can change with depth. The highest salinities are in surface waters of the tropics (either side of the equator). In deeper waters (below 500 m), the salinity is slightly lower than at the surface (Data from World Ocean Atlas 2018).

THE STORY CONTINUES

With all this progress, you would think that the puzzle of ocean salinity has been solved. But this is not the case. While Forchhammer's idea about the constant composition of sea water has been enormously useful, there are actually small but measurable differences in the salt composition across regions of the ocean. Although these differences are small, they are important if we want to accurately describe the properties of seawater. So, scientists are now updating how they calculate ocean salinity, taking into account that the salts in seawater are not so constant after all [3]. After over 150 years, the story continues to unfold. There is more to salt than you might think. Keep that in mind next time a wave takes you by surprise and you get a mouthful of salty water!

ACKNOWLEDGMENTS

This publication was supported by a grant from the Smed Foundation to AWV and Independent Research Fund Denmark Grant No. 9040-00266B to CS. Figures were designed and created with support from Pernille W. Rasmussen.

REFERENCES

1. Forchammer G. 1865. On the composition of sea-water in the different parts of the ocean. *Philos. Transact. R. Soc. London* 155:203–62. doi: 10.1098/rstl.1865.0004
2. Millero F. J. 2010. History of the equation of state of seawater. *Oceanography* 23:18–33.
3. McDougall, T. J., Jackett, D. R., Millero, F. J., Pawlowicz, R., and Barker, P. M. 2012. A global algorithm for estimating absolute salinity. *Ocean Sci.* 8:1123–34. doi: 10.5194/os-8-1123-2012

SUBMITTED: 14 November 2022; **ACCEPTED:** 15 November 2023;
PUBLISHED ONLINE: 11 December 2023.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Luisa I Falcon and Florence Barbara Awino

CITATION: Stedmon CA and Visser AW (2023) Why Is the Sea Salty and Does It Matter? Front. Young Minds 11:1097831. doi: 10.3389/frym.2023.1097831

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: 14
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.

SEBASTIAN, AGE: 14
I like sports, reading, math, physics, and all things space!

AUTHORS

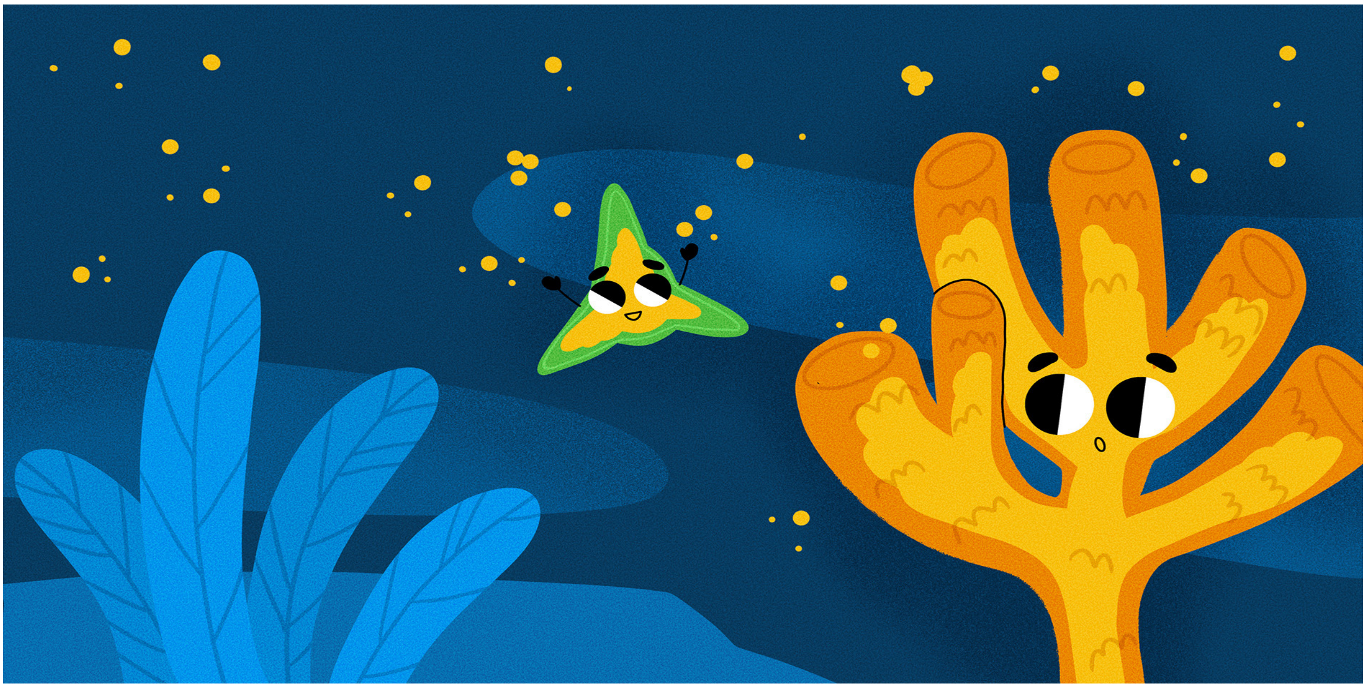
COLIN A. STEDMON

Prof. Colin Stedmon is a chemical oceanographer at the Technical University of Denmark. He obtained his Ph.D. from the University of Copenhagen in 2004. His current research focuses on Arctic marine biogeochemistry. This essentially involves studying the chemical composition of seawater and collaborating with experts in marine physics and biology to understand how the oceans function and in particular how the Arctic is changing. He mostly enjoys the detective work. Looking for patterns in the data, finding explanations for why they are there and contributing to an understanding of how the oceans function. *cost@aqua.dtu.dk

ANDRÉ W. VISSER

Prof. André Visser is a physical oceanographer at the Technical University of Denmark. He has a Ph.D. in oceanography from the State University of New York. His research interests lie where physics and biology meet. In particular, his research is focused on uncovering the strategies that plankton have evolved to thrive in the ocean, describing these with mathematics to create models that help us understand the role they have on a global scale.

EARTH SCIENCES
Published: 11 December 2023
doi: 10.3389/frym.2023.1180915



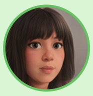
THE ANTARCTIC SILICON TRAP

Ivia Closset[1,2*] *and Lucie Cassarino*[3*]

[1] *Marine Observatories and Measurement Techniques, Finnish Meteorological Institute, Helsinki, Finland*
[2] *Marine Science Institute, University of California, Santa Barbara, Santa Barbara, CA, United States*
[3] *Institut Universitaire Européen de la Mer, LEMAR Laboratory Plouzané, Université de Bretagne Occidental, Plouzané, France*

YOUNG REVIEWERS:

ALISSAR
AGE: 14



ANTONELLA
AGE: 13

FLORENCIA
AGE: 13

The Southern Ocean, the ocean encircling Antarctica, has been described by explorers as cold, empty, and dangerous. Despite this, it is a paradise for tiny algae called diatoms that are crucial players in the regulation of our climate. Why are these tiny organisms so happy in this cold and far away ocean? Diatoms have a solid shell made of a glass-like material called silica, so they need to find silicon in surface waters to build it. The Southern Ocean is the perfect place for diatoms because it is full of silicon compared to the other oceans. This is due to a special phenomenon called the silicon pump, which makes the Southern Ocean a giant trap for silicon. In this article, we point out the central role of the Southern Ocean in the regulation of Earth's climate and how it controls the distribution of silicon and the wellbeing of diatoms in Antarctic waters.

ANTARCTICA AND THE OCEAN CONVEYOR BELT

Seventy percent of the surface of our beautiful blue planet is covered by oceans. It is therefore not surprising that the oceans play a key role in the fragile balance of Earth's climate. For example, water at the surface of the ocean absorbs heat from the sun and carries this heat around the planet using ocean currents. These currents also transport nutrients that are important for life.

The planet's strongest current is called the **Antarctic Circumpolar Current (ACC)** and it is so wide that, by itself, it makes up an entire ocean named the Southern Ocean. The ACC flows eastward in the southern hemisphere, circling Antarctica, and connects the Atlantic, Pacific, and Indian oceans together (Figure 1A). The Southern Ocean plays a key role in Earth's climate by absorbing a fraction of the carbon dioxide (CO_2) produced by human activities, and therefore helps to balance the accumulation of this gas in the atmosphere [1].

ANTARCTIC CIRCUMPOLAR CURRENT (ACC):

The Antarctic Circumpolar Current (ACC) is one of the strongest current in the world and it encircle Antarctica.

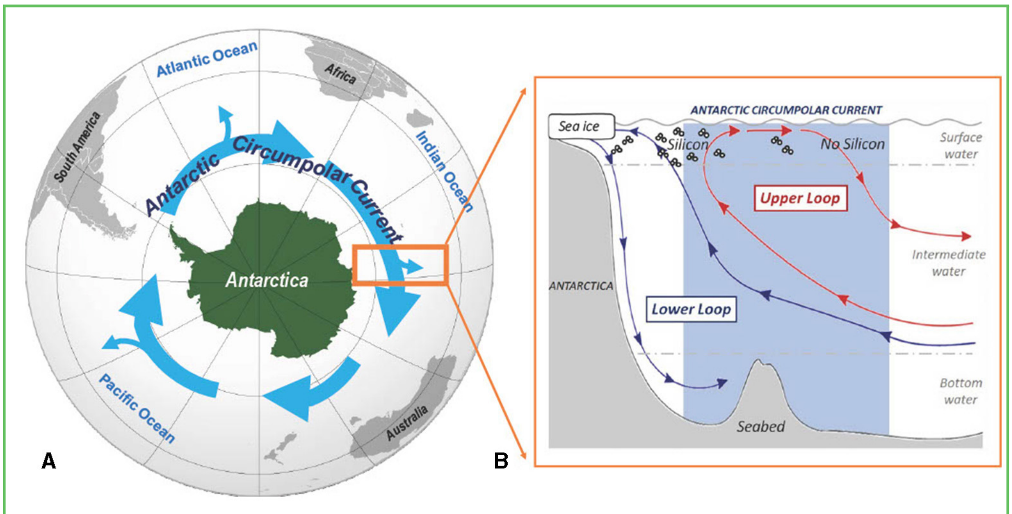


Figure 1

Figure 1

(A) The strong Antarctic circumpolar current flows clockwise (eastward) around Antarctica. Some water escapes northward into the Atlantic, Pacific, and Indian oceans. **(B)** Water from the deep ocean is brought to the surface in the Southern Ocean, and it brings lots of silicon with it. As the current flows northward, the silicon is used by diatoms, which leave no silicon in the water that escape the Southern Ocean through the upper loop of the ocean conveyor belt (red). In blue is the water that encounters sea ice dives to the bottom of the ocean (Figure credit for **A**: AntarcticGlaciers.org).

The ACC is considered to be the core of a much larger system of currents that flow all around the planet; a phenomenon called the **overturning circulation**, or the ocean conveyor belt. Just like a pulsing heart, the Southern Ocean collects water from the deep layers of the Atlantic, Pacific, and Indian oceans and brings it to the surface. This seawater interacts with the atmosphere and with sea ice and feeds many living organisms. Then the water circulates in two ways, forming two different loops (Figure 1B). In the lower loop, seawater moves southward toward Antarctica. It cools down when meeting sea ice and sinks to the very bottom of every ocean (see also this Frontiers for Young Minds article). In the upper loop, seawater moves northward and eventually dives to intermediate depths (around 1,000 m). These intermediate waters are then transported very far north. They even cross the equator and eventually reach the surface in warmer regions of the ocean [2]. The ocean conveyor belt is very important because it connects the waters at the surface to the intermediate and bottom layers of the ocean, and exchanges heat and nutrients between the Southern Ocean and the rest of the globe.

OVERTURNING CIRCULATION

It is the global ocean current that travel around all continent.

As you will learn, a small change in the unique environment of the Southern Ocean could have strong consequences on the ability of the ocean to both distribute nutrients throughout the oceans and to regulate the climate.

WHY IS ANTARCTICA A DIATOM PARADISE?

Tiny algae live in the surface water of the ocean. There, they absorb nutrients and combine them with sunlight to produce energy and to grow. This process is called photosynthesis, and it is very important for us because photosynthesis uses up CO_2 and releases oxygen, making life possible on Earth (for more information on photosynthesis in the ocean, see this Frontiers for Young Minds article). While there are many different algae in the world's waters, one specific group, called **diatoms**, thrives in the Southern Ocean's cold waters (Figure 2). There, diatoms can make up more than 90% of the total amount of algae in the surface ocean [3].

DIATOMS

A group of small, single-celled algae that can capture silicon from water and light from the sun to build a transparent shell called frustule.

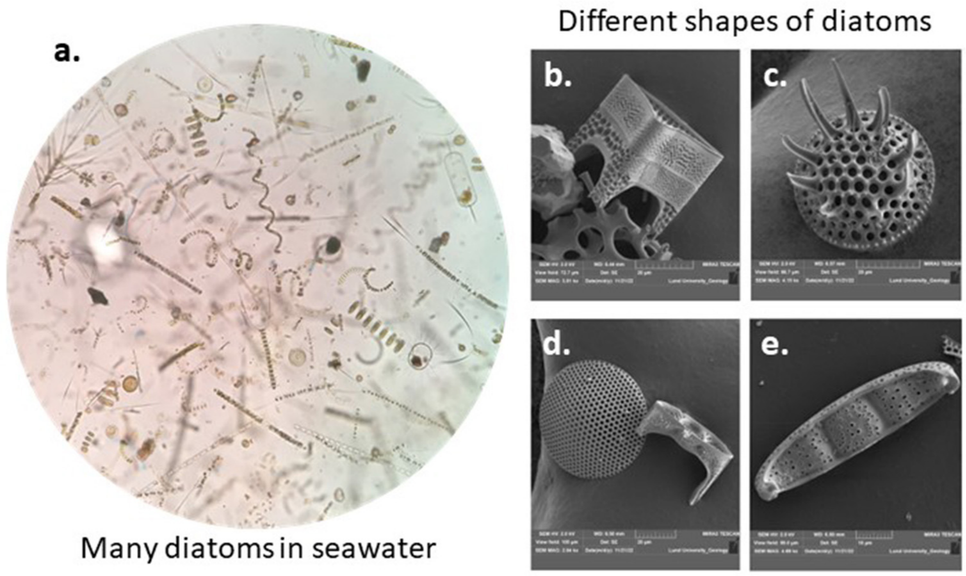


Figure 2

Figure 2

(a) There are many diatoms in one drop of Antarctic seawater, but they can be seen only using a microscope. **(b–e)** With a very powerful microscope, the delicate features of the frustule, such as holes and spines, can be observed for each individual diatom species.

Diatoms measure <1 mm in size and are encased in a hard shell, called a **frustule**, made of **silica** (the scientific word for glass). Frustules are like beautifully decorated tiny glass boxes and make diatoms unique among all the algae. Billions of diatoms grow during spring and summer at the surface of the ocean, and as they do they absorb CO_2. Thanks to their frustule, they are quite heavy (compared to other algae) and they sink to the bottom of the ocean, carrying with them all the carbon they took up in the surface waters. This process is called the **biological pump of carbon** because the carbon is "pumped" from the atmosphere and stored at the bottom of the ocean for a very long time [3].

FRUSTULE

Skeletal structure of diatoms made of silica.

SILICA

A mineral that exists in various forms including sand, glass, and opal.

BIOLOGICAL PUMP OF CARBON

A set of processes, including photosynthesis performed by algae, that trap or "pump" CO_2 from the atmosphere into the ocean, where it is stored for a long time.

SILICON

Chemical element that is found in silica, rocks, sand, glass, and opal.

Since they need **silicon** to make their glassy frustule, diatoms depend strongly on the availability of silicon within their environment. Diatoms are so voracious that they can use all the silicon in the surface waters, leaving very little behind. When they have exhausted all the silicon around them, diatoms die and sink toward the bottom of the ocean, carrying all the silicon and carbon with them. Without silicon in the seawater, diatoms cannot grow. Thankfully for diatoms, the Southern Ocean is a paradise because it is the ocean region where silicon is the most abundant. But why is that?

HOW DOES THE SOUTHERN OCEAN TRAP SILICON?

Diatom frustules are heavy, making diatoms sink faster than other tiny algae, although it can take them several days to several months to reach the bottom of the ocean. While they are sinking down through the ocean, their frustules progressively break down and dissolve, releasing the silicon back to the ocean in a form that can be used as a nutrient by other organisms. This process is slow and occurs mostly in the intermediate and bottom parts of the ocean. Scientists think that at least half of the diatoms dissolve between the surface of the ocean and 2,000 m depth [4]. Interestingly, because of this slow breakdown of diatoms, most of the silicon is recycled in the ocean layers where the water is flowing toward Antarctica. The silicon then travels back to the surface waters, where it will be consumed by new diatoms, closing the circle. Diatoms in the Southern Ocean therefore always have enough silicon to grow. The combination of these two processes: (i) transforming silicon (dissolved in seawater) into silica (within the frustule) at the surface, and (ii) bringing it to the deep ocean where it is recycled is called the **silicon pump** (Figure 3).

SILICON PUMP

This is the transfer of silica from the surface of the ocean to the deep layer due to diatom.

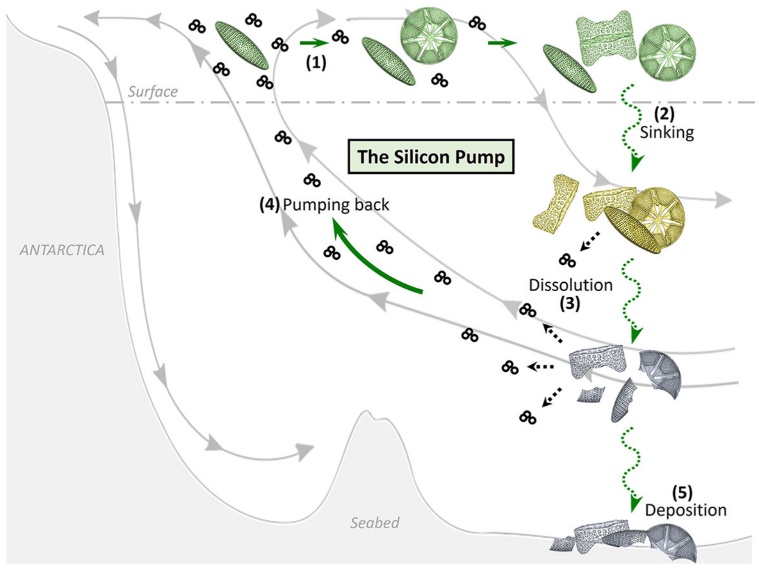


Figure 3

Figure 3

The silicon pump in the Southern Ocean. Silicon dissolved in seawater is used by diatoms at the surface of the ocean, to grow **(1)**. When they die, diatoms sink **(2)**, break down and dissolve **(3)**, releasing the silicon back to the ocean. This recycled silicon is brought back to the surface **(4)** by the ocean circulation that is unique to the Southern Ocean. The diatoms that did not dissolve in the water reach the bottom of the ocean and accumulate to the seabed **(5)** to form the opal belt.

Currently, the silicon pump is very efficient and keeps most of the silicon in the Southern Ocean. As the surface current in the Southern Ocean flows northward, diatoms progressively consume all the silicon in the seawater. Therefore, when this water dives within the upper loop of the conveyor belt and escapes Antarctica, it contains almost no silicon. This low-silicon water is transported to the other oceans via the conveyor belt, and therefore will reduce or prevent the growth of diatoms there.

THE OPAL BELT: THE ANTARCTIC'S UNIQUE SEDIMENTS

Only the diatoms that are not dissolved during their journey through the deep ocean reach the bottom of the ocean and the sediments. There, they accumulate and remain buried for a very long time (up to several million years). In the Southern Ocean, because diatoms are so numerous and active in the surface water, they make up the majority of particles that sink toward the bottom of the ocean. As a result, some regions of the ocean seabed can be made up of more than 80% diatom fossils [5] and form an extremely unique circle of silica-rich sediment all around Antarctica called the opal belt.

CONCLUSION: IS THE ANTARCTIC SILICON TRAP LEAKING?

The giant silicon trap around Antarctica holds more than half of the total amount of silicon existing in all the oceans. Scientists estimate that, today, very little of the silicon that enters the Southern Ocean (<5%) can escape this ocean trap, while other nutrients, such as nitrate and phosphate, escape more easily and are transported toward other regions of the ocean [4].

Evidence from diatoms buried within the Antarctic has shown that, at some periods in the past, the silicon trap has been weaker than we observe today. The lower efficiency of the trap allowed silicon to "leak" from the Southern Ocean and to be transported to the other oceans, through the upper loop of the conveyor belt. When more silicon escapes the Southern Ocean and is redistributed to the surface waters of other oceans, it allows more diatoms to grow and therefore more CO_2 to be removed from the atmosphere via the biological pump of carbon. If this is true, it could partly explain the transitions between ice ages, when the Earth was much colder than today, and warmer periods like we have now. For example, the last ice age, which ended about 15,000 years ago, would have been characterized by a leaking silicon trap in Antarctica, allowing more diatoms to pump CO_2 into the Atlantic, Pacific, and Indian oceans. The reduction of CO_2 in the atmosphere from diatom pumping makes the atmosphere cooler because there is less CO_2 capturing and storing heat, instead the heat is released out in space.

Of course, there is still much that scientists do not know about the silicon trap and its role in the regulation of Earth's climate. Studying this topic involves working in the very cold, wild Antarctic environment, which, as you can imagine is quite challenging. However, scientists continue to do this important research, because despite the close link between the carbon and silica cycle, the models that predict future climate lack the silica component as it is a complex cycle.

ACKNOWLEDGMENTS

This manuscript is part of a series of 6 manuscripts about the marine silicon cycle by the ECR SILICAMICS group. We thank the SILICAMICS ECRs consortium for its enthusiasm for putting this project together. We warmly thank the three young reviewers and their mentor for their sensible comments that greatly improved this manuscript. This work was supported by grants from the National Science Foundation #OCE-2048998 (IC) and from the European Union's Horizon 2020 research and program Marie Skłodowska-Curie #899546.

REFERENCES

1. Lenton, A., Tilbrook, B., Law, R. M., Bakker, D., Doney, S. C., Gruber, N., et al., 2013. Sea-air CO2 fluxes in the Southern Ocean for the period 1990-2009. *Biogeosciences* 10:4037–4054. doi: 10.5194/bg-10-4037-2013
2. Sarmiento, J. L., Gruber, N., Brzezinski, M. A., Dunne, J. P. 2004. High-latitude controls of the thermocline nutrients and low latitude biological productivity. *Nature* 427:56–06. doi: 10.1038/nature02127
3. Tréguer, P., Bowler, C., Moriceau, B., Dutkiewicz, S., Gehlen, M., Aumont, O., et al. 2018. Influence of diatom diversity on the ocean biological carbon pump. *Nat. Geosci.* 11:27–37. doi: 10.1038/s41561-017-0028-x
4. Holzer M., Primeau, F. W., DeVries, T., Matear, R. 2014. The Southern Ocean silicon trap: data-constrained estimates of regenerated silicic acid, trapping efficiencies, and global transport paths. *J. Geophys. Res.* 119:313–331. doi: 10.1002/2013JC009356
5. Chase, Z., Anderson, R. F., Fleisher, M. Q., Kubik, P. W. 2003. Accumulation of biogenic and lithogenic material in the Pacific sector of the Southern Ocean during the past 40,000 years. *Deep-Sea Res.* 50:799–832. doi: 10.1016/S0967-0645(02)00595-7

SUBMITTED: 06 March 2023; **ACCEPTED:** 20 November 2023;
PUBLISHED ONLINE: 11 December 2023.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Carlos Andres Henríquez-Castillo and Loai Aljerf

CITATION: Closset I and Cassarino L (2023) The Antarctic Silicon Trap. Front. Young Minds 11:1180915. doi: 10.3389/frym.2023.1180915

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

ALISSAR, AGE: 14

I spend the summertime swimming, riding around town, and playing in the park. My childhood was idyllic, and I have many fond memories of those carefree days. I was involved in a lot of extracurricular activities, including the school band and the drama club. I am a member of some green sorority clubs and am involved in a lot of campus activities. I hope to land some small roles in independent films and commercials and also would like to do some modeling work and appearing in some TV shows and movies.

ANTONELLA, AGE: 13

Antonella is a very charismatic girl who loves the English language. In her daily life she enjoys reading, listening to music and practicing English with her sister. Antonella has an inventive mind and boundless creativity making her a whirlwind of scientific exploration.

FLORENCIA, AGE: 13

Florencia is a very extroverted girl who loves life. Her hobby is to listen to music in English, and to understand the meaning of what each song wants to transmit. Florencia's observant nature and meticulous approach helps her unravel nature's secrets.

AUTHORS

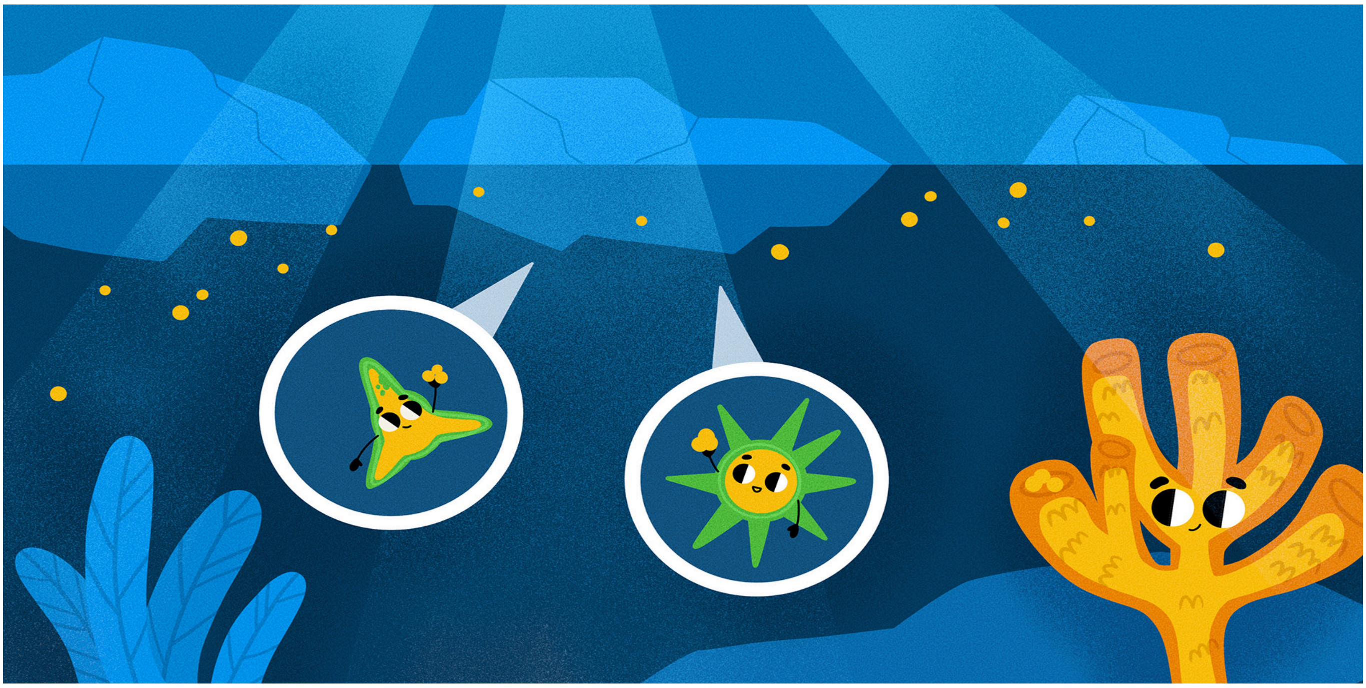
IVIA CLOSSET

I am a marine biogeochemist and I have always been obsessed by the mysteries dwelling in the unseen and wildest part of the ocean. Science has quickly become a way for me to experience and understand the delicate balance of the world around us. In my research, I mainly use stable isotopes to track modern and past ocean processes, such phytoplankton activity or organic matter recycling, all of this with a strong focus on the silicon cycle and the Southern Ocean. I have been working using various types of samples, from cold and warm seawater, delicate diatoms, frozen sea ice and muddy sediments from the deep seabed that I have collected in many places in collaboration with people from many countries. Now, I am involved in marine research using gliders (a type of underwater robots) and I will conduct experimental observations using these gliders to monitor the health of the sea. *ivia@ucsb.edu

LUCIE CASSARINO

My research interests are modern marine biogeochemical cycles with a focus on the silicon cycle. It consists of understanding how marine nutrients are distributed in the ocean, giving information on the wellbeing of organisms that need silicon to survive, such as diatoms, siliceous Rhizaria and siliceous sponges. My work combines many fields such as chemistry, geochemistry, physics, biology, and geology to get the best pictures of the cycles. I also use very fine chemical tools (stable isotopes) to understand the influence of the ocean dynamic on phytoplankton distribution, to understand how siliceous organisms build their skeleton, and to help scientists looking at the past (from sediment fossils). My research has a particular interest in the polar environments but also relies on other field data and laboratory experiments. I am at the moment creating an observatory that will be deployed in arctic waters to follow concentration of nutrients and the physical parameters in real time. *Lucie.cassarino@univ-brest.fr

BIODIVERSITY
Published: 01 December 2023
doi: 10.3389/frym.2023.1172756



SILICIFIERS: THE GLASSY CREATURES OF THE OCEAN

***Alessandra Petrucciani*[1*†], *Natalia Llopis Monferrer*[2,3*†] *and María López-Acosta*[4*†]**

[1] *Laboratory of Algal and Plant Physiology, Department of Life and Environmental Sciences, Università Politecnica delle Marche, Ancona, Italy*

[2] *CNRS, UMR7144 Adaptation and Diversity in Marine Environment (AD2M) Laboratory, Ecology of Marine Plankton Team, Station Biologique de Roscoff, Sorbonne University, Roscoff, France*

[3] *Monterey Bay Aquarium Research Institute, Moss Landing, CA, United States*

[4] *Instituto de Investigaciones Marinas (IIM), CSIC, Vigo, Spain*

[†] *These authors have contributed equally to this work and share first authorship.*

YOUNG REVIEWERS:


MUHAMMAD
AGE: 14


SEBASTIAN
AGE: 14

Silicon is one of the most abundant chemical elements in the universe. On Earth, it forms sediments, minerals, and rocks. In the ocean, silicon is found in a dissolved form that can be used by many organisms to grow. You probably know that humans use calcium to build their skeletons, but did you know that there are creatures capable of forming skeletons out of silicon? Organisms capable of capturing dissolved silicon from the environment and transforming it into glassy skeletons are called silicifiers. Silicifiers use a unique process called biosilicification to create their skeletons. In the marine ecosystem, silicifiers come in a surprising variety of shapes and sizes, and they include, among others, diatoms, rhizarians, and sponges.

These three groups, so diverse and yet so similar, are essential to the health of the oceans.

LIVING IN A GLASS HOUSE

Among the elements that you may have heard about in chemistry class, **silicon** is one of the most abundant on our planet. Did you know that silicon is the element that forms glass? In nature, glass, also known as **silica**, is part of what makes up the sand of the beaches that people love to walk on when they are on holidays. Humans use silicon for many purposes. For example, it is used to produce chips for computers and smartphones, medicines to improve skin healing and prevent bone damage, and lenses for eyeglasses, microscopes, and telescopes. However, when it comes to making things out of glass, humans are less efficient than certain other organisms. While the industrial glass-production process needs to reach very high temperatures, on the order of 1,000°C (1,800°F), some organisms can capture dissolved silicon from water and transform it into beautiful glassy structures, at regular temperatures!

Why would organisms want to have a silica skeleton? These walls of glass can protect organisms against predators and give them structural support, thanks to the hardness and elasticity of silicon. The ability to build glass houses is called **biosilicification**, and organisms that can do so are called **silicifiers**. Silicifiers are essential for the proper functioning of the ocean ecosystem. The processes carried out by these jewels of nature are full of mystery, and scientists are still striving to understand them, as they can serve as inspiration for the glass industry and for the production of new tiny structures thinner than a human hair called nanomaterials [1]. There are many silicifiers in the ocean, and we will introduce you to three of the most important ones.

DIATOMS—GLASS-COVERED ALGAE

When you think of algae, you probably imagine green leaves floating in the sea. The oceans are also home to a multitude of tiny organisms, called **microalgae**, which can only be observed with a microscope. Microalgae often have just a single cell, but sometimes they can form small, multicellular colonies. Like all plants, microalgae have tiny structures called **chloroplasts**, which help them to convert sunlight into energy through photosynthesis. Diatoms are the most abundant class of microalgae, and they are famous for their ability to capture silicon from seawater to build transparent glass skeletons (Figures 1A, D). This glass-containing cell wall, called the **frustule**, is decorated with a multitude of pores, forming regular patterns of exceptional delicacy and beauty. But why spend vital energy to build such a complex structure? This skeleton, which is hard but flexible, can protect diatoms

SILICON

Element 14 of the periodic table that conducts electricity very easily and is used to build computers and electronic devices.

SILICA

Compound formed by silicon and oxygen. It is very abundant in rocks and forms the sand of beaches.

BIOSILICIFICATION

Process made by living organisms that capture dissolved silicon in water and transform it into beautiful and robust glassy skeletons.

SILICIFIERS

Organisms that create silica skeletons, including diatoms, Rhizaria, and sponges, through the process called biosilicification.

MICROALGAE

A tiny plant-like living thing that floats in the water and makes food from sunlight.

CHLOROPLAST

A unique structure found in plant cells that can convert sunlight into energy, in a process called photosynthesis.

FRUSTULES

Glass walls covering the diatoms like a sandwich. The walls take many shapes and are highly decorated.

from the jaws of their predators: just as cows eat grass, there are tiny animals in the oceans that feed on diatoms. In addition, the glass skeletons can prevent attacks by viruses, improve nutrient absorption, and guide sunlight into the chloroplasts. Living surrounded by glass has allowed diatoms to thrive in all kinds of environments, from oceans to freshwater. Diatoms can live in seawater, in the sediments at the bottom of the ocean, and they can even survive in sea ice [2].

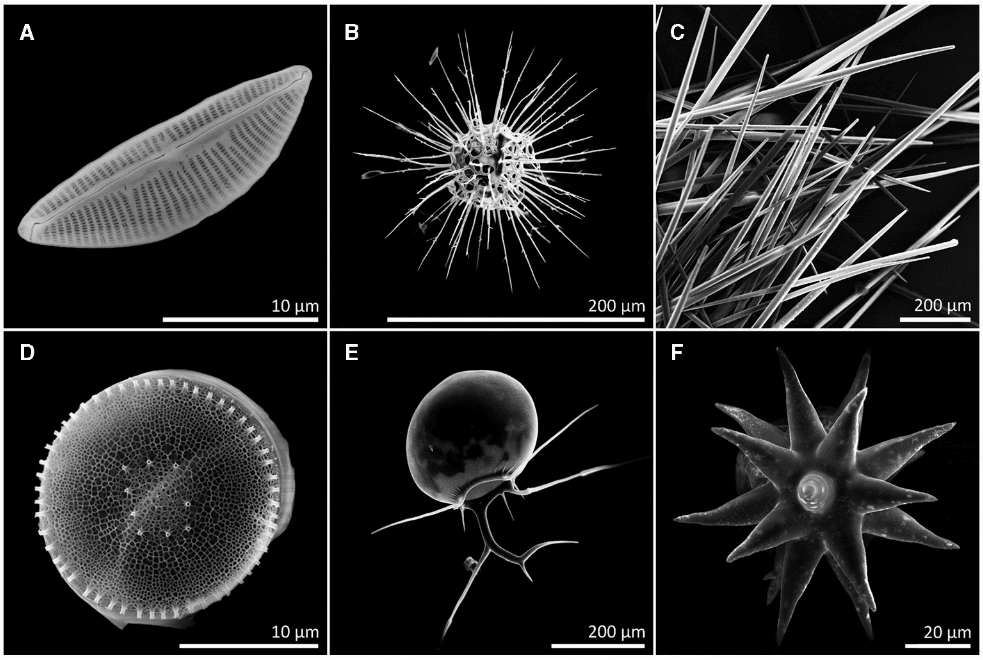


Figure 1

Figure 1

Images of silicifiers taken with a powerful microscope called a scanning electron microscope: **(A)** diatom; **(B)** rhizaria; **(C)** sponge spicules; **(D)** diatom; **(E)** rhizaria; and **(F)** sponge spicules.

RHIZARIA—BEYOND PHOTOSYNTHESIS

Marine rhizarians are unicellular organisms that range in size from several micrometers to a few millimeters (for those that form colonies) [3]. Many are larger than diatoms and can be seen with the naked eye. Rhizarians are fearless of extreme temperatures, which is why they can be found in all oceans, from tropical to polar climates. Unlike diatoms, which need light to exist, rhizarians can be found at all depths of the ocean. Those dwelling on the surface may even associate with microalgae for purposes of nourishment or protection, in an interaction called symbiosis.

Like diatoms, rhizarians can capture the silicon dissolved in seawater to form glassy skeletons with very diverse geometric shapes—such as pyramids, snowflakes, stars, spheres, and many others—which makes them true microscopic treasures (Figures 1B, E). Rhizarians can extend pseudopods, which are numerous arm-like projections, through their skeletons, using them to capture small prey—from bacteria and remnants of dead organisms to other planktonic organisms.

SPONGES—THE OLDEST ANIMALS ON EARTH

Silicon is not restricted to single-celled organisms. Sponges, which are multicellular aquatic animals, also use silicon to build their skeletons. Sponges are the oldest animals on Earth. They do not have organs like humans do. Instead, they have specialized cells for feeding, reproduction, or defense. Most sponges live in the ocean, but some live in rivers and lakes. They live fixed in one place, like plants, and do not move. Sponges capture their food by filtering large amounts of water and collecting tiny suspended particles, from bacteria and tiny remnants of dead organisms to small plankton.

Sponges come in many shapes and sizes: from tiny crusts measuring only a few millimeters, to sophisticated branched and cup-shaped forms measuring in meters. It is their skeletons that allow them to have such distinct shapes and enable them to resist strong currents caused by waves or tides. Most sponge species capture dissolved silicon from seawater and build a silica skeleton composed of millions of microscopic pieces called **spicules** (Figures 1C, F) [4]. However, there are some spicules that are large enough to be seen directly with the naked eye. Sponges are the only multicellular animals to have siliceous skeletons.

SPICULES

Each of the small glassy pieces that form the skeleton of a sponge. Spicules take forms varying from simple needle-shaped rods to highly ornamented star-shaped or hook-shaped pieces.

WHY ARE SILICIFIERS IMPORTANT IN THE OCEAN?

Silicifiers can live either floating on the surface, in the deep ocean waters, or attached to the seafloor, depending on the species. Partly because they can live almost everywhere, silicifiers are involved in many important ocean processes. One of their key roles is controlling the process of silicon reuse in ocean ecosystems. Silicifiers consume dissolved forms of silicon from the seawater to build their glassy skeletons. When silicifiers die, their skeletons sink toward the ocean floor, since they are heavy. As they sink, most of the glass skeletons dissolve and are recycled into the water, becoming dissolved silicon that can be used by other silicifiers. The fraction of the glass skeletons that resists dissolving reaches the seafloor, where it can either remain, covering the ocean floor with a silicon blanket, or dissolve and return to the upper layers of the ocean, carried by ocean currents. The skeletons of silicifiers like sponges, which already live on the ocean floor, also end up in the sediments where they undergo the same processes as the skeletons of diatoms and rhizarians—ultimately recycling their glassy spicules into dissolved silicon [5]. Despite the fragile appearance of the skeletons of silicifiers, some of them are very resistant over time. Their ancestors can be found in layers of sediment that are several million years old (Figure 2)! These fossils are studied by scientists called micropaleontologists, who try to find evidence telling them what the environmental conditions of the past were like.

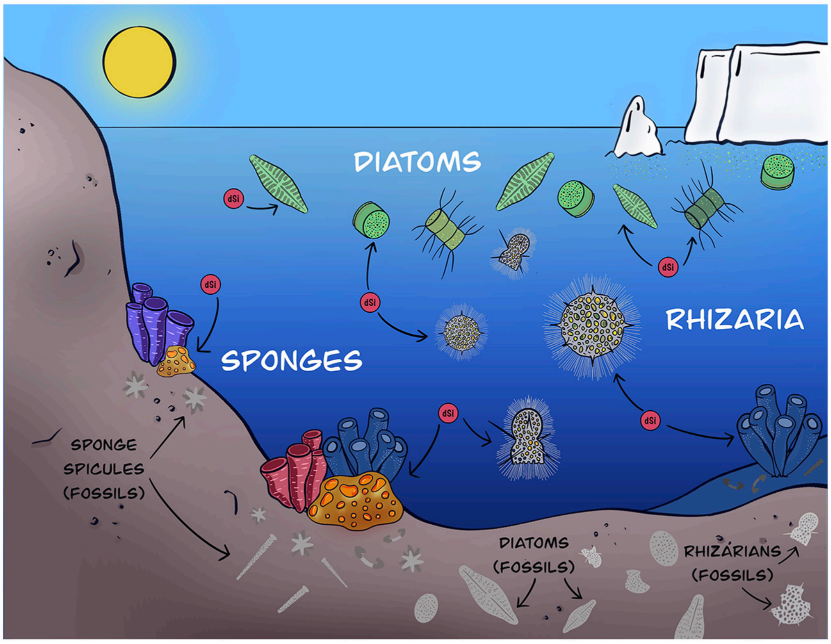


Figure 2

Figure 2

Silicifiers in the ocean. Dissolved silicon (dSi) in the ocean water is used by silicifiers to build their protective structures: the frustules of diatoms, the skeletons of rhizarians, and the spicules of sponges. When silicifiers die, their protective structures dissolve into the seawater, where the silicon can be reused by other organisms, or the skeletons can remain in the ocean sediments as fossils.

STUDY SILICIFIERS TO PROTECT THEM

Despite having impressive glassy armors, silicifiers are not immune to the effects of the ongoing climate change. In a changing ocean, the availability of silicon and other nutrients varies continuously, affecting the health of silicifiers. The study of these tiny and difficult-to-access organisms is a challenge for biologists and oceanographers. However, we need to figure out how silicifiers adapt to climate change. In the end, we can conserve only what we know and understand.

ACKNOWLEDGMENTS

This article is part of a series of 6 manuscripts about the marine silicon cycle put together by the ECR SILICAMICS group. We thank the SILICAMICS ECRs consortium for its enthusiasm in putting this project together. Authors also thank P. Elies and V. Foulon for their excellent microscopic work in taking the pictures used for Figures 1B, C, E, F. Special thanks to Mia, Yannis, Mia H., and two young reviewers for taking time out of their busy weeks to read this article and give us their invaluable feedback. AP received funding from the European Union's Horizon research and innovation actions programme under grant agreement No 101083355 (project DESIRED). NL received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101064167 (MSCA postdoctoral fellowship Si-ORHIGENS). ML-A received funding from the Xunta de Galicia for her postdoctoral fellowship (IN606B-2019/002, ARISE) and grant (IN606C-2023/001, SPICA).

REFERENCES

1. Mcheik, A., Cassignon, S., Livage, J., Gibaud, A., Berthier, S., and Lopez, P. J. 2018. Optical properties of nanostructured silica structures from marine organisms. *Front. Marine Sci.* 5:123. doi: 10.3389/fmars.2018.00123
2. Seckbach, J., and Kociolek, P. 2011. *The Diatom World.* Vol. 19. Cham: Springer Science & Business Media.
3. Boltovskoy, D., Anderson, O. R., and Correa, N. 2017. "Radiolaria and phaeodaria," in *Handbook of the Protists*, eds. L. Margulis, M. Melkonian, D. J. Chapman, and J. O. Corliss (Cham: Springer).
4. Van Soest, R. W. M., Boury-Esnault, N., Vacelet, J., Dohrmann, M., Erpenbeck, D., De Voogd, N. J., et al. 2012. Global Diversity of Sponges (Porifera). *PLoS ONE* 7:e35105. doi: 10.1371/journal.pone.0035105
5. Tréguer, P. J., Sutton, J. N., Brzezinski, M., Charette, M. A., Devries, T., Dutkiewicz, S. et al. 2021. Reviews and syntheses: the biogeochemical cycle of silicon in the modern ocean. *Biogeosciences* 18:1269–1289. doi: 10.5194/bg-18-1269-2021

SUBMITTED: 23 February 2023; **ACCEPTED:** 15 November 2023;
PUBLISHED ONLINE: 01 December 2023.

EDITOR: Sanae Chiba, North Pacific Marine Science Organization, Canada

SCIENCE MENTORS: Luisa I. Falcon and Dalaq Aiysha

CITATION: Petrucciani A, Llopis Monferrer N and López-Acosta M (2023) Silicifiers: The Glassy Creatures of the Ocean. Front. Young Minds 11:1172756. doi: 10.3389/frym.2023.1172756

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

MUHAMMAD, AGE: 14

The turning point in my curiosity came when I secured first place in my grade 3 science project. It was about photosynthesis, which I chose after knowing the fact that plants are universal food makers. The science textbook of every grade always familiarized me about the magical wonders behind my daily life's surroundings.

SEBASTIAN, AGE: 14
I like sports, reading, math, physics, and all things space!

AUTHORS

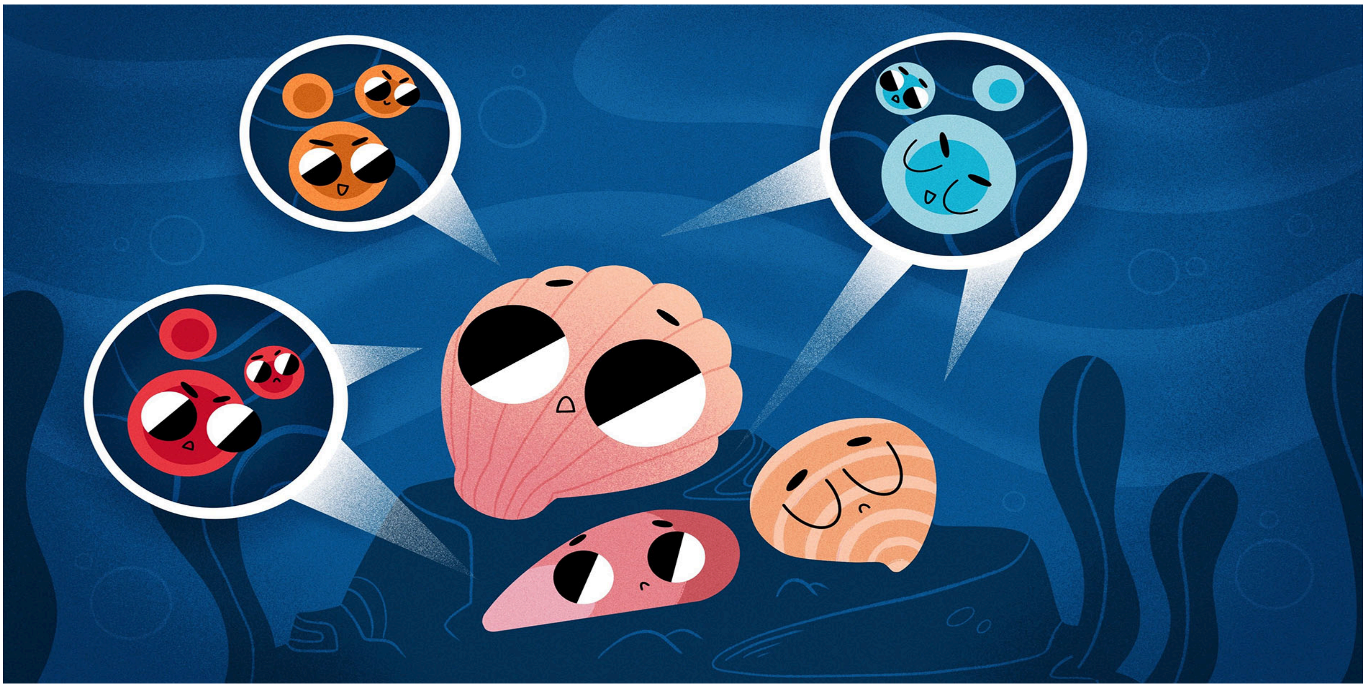
ALESSANDRA PETRUCCIANI
I am a marine biologist and my research interests focus on the biology of diatoms—an extraordinary group of unicellular photosynthetic organisms that are an abundant type of microalgae. During my Ph.D., I studied the structure, function, and evolution of the diatom frustule, particularly the way it helps diatoms to float and protect themselves against predators. Now I am working on the response of diatoms to climate change. *a.petrucciani@staff.univpm.it

NATALIA LLOPIS MONFERRER
I am a marine ecologist and I am passionate about understanding the role of plankton in the ocean. I was fascinated by the beauty of plankton and decided to study the role of rhizarians in the ocean's silicon cycle. I was able to collect, observe, and study these planktonic jewels during four oceanographic voyages, in the Mediterranean, the Atlantic and Pacific Oceans, and the Ross Sea, Antarctica. I am now working to better understand the biosilicification process of these organisms. *natalia.llopis@sb-roscoff.fr

MARÍA LÓPEZ-ACOSTA
I am a marine ecologist interested in the role of bottom-dwelling ocean organisms in ocean nutrient cycling, with a special interest in silicon. My model organisms are sponges, which I have been studying for more than a decade and still find as fascinating as the first day. I have studied sponges in shallow waters of the North Atlantic Ocean and Mediterranean Sea by diving, and in deep waters of the Norwegian Sea, Barents Sea, and North Atlantic Ocean using underwater robots. I am now studying the effects of human impacts on silicon recycling in sponges and other silicifiers. *lopezacosta@iim.csic.es

frontiers | Frontiers for Young Minds

BIODIVERSITY
Published: 28 November 2023
doi: 10.3389/frym.2023.1129218



CONTAGIOUS CANCERS THAT CAN SPREAD BETWEEN OCEAN ORGANISMS

Alicia L. Bruzos[1,2] *and Seila Diaz*[3*]

[1] *Genetics and Genomic Medicine Department, University College of London, London, United Kingdom*
[2] *Mosaicism and Precision Medicine Laboratory, The Francis Crick Institute, London, United Kingdom*
[3] *Department of Biology, ECOMARE, Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal*

YOUNG REVIEWERS:


ARIA
AGE: 11


SIA
AGE: 10

Cancer is a disease that occurs when cells multiply uncontrollably. It can affect species on land or in water. Normally, cancer is not contagious; it only affects the organism in which it originates. However, recently, a new type of contagious cancer was found in some ocean animals. Contagious cancers have been discovered in clams, cockles, and mussels around the world. These cancer cells leave the body of the organism where they originated, survive in seawater, and then infect other individuals. In this article, we will tell you what makes contagious cancers different from normal cancers, the species in which contagious cancers have been detected, and the great importance of studying these rare cancers.

CANCER: UNCONTROLLED CELL DIVISION

Pretty much everyone has heard of a terrible disease called cancer. In humans, specific types of cancer can affect organs like the brain,

MUTATION

Any change in the genetic material of an organism, specifically a modification of its DNA sequence.

CONTAGIOUS

Something can be passed from one person to another, like a cold or a flu when you're close to someone who's sick.

BIVALVES

Aquatic organisms with bodies that are enclosed by two "valves", which are commonly known as shells. Examples include clams and mussels.

HAEMOLYMPH

Fluid that circulates within the bodies of some invertebrates such as insects, arachnids, and mollusks. Its function is similar to blood.

MITOSIS

The process by which a single cell divides into two cells, which involves replicating and splitting up the DNA.

DNA

Deoxyribonucleic acid, the molecule that contains the genetic information of cells.

lungs, or skin. The body's normal, healthy cells only divide as much as necessary, but cancer results from a massive, out-of-control multiplication of cells. Typically, cancers are caused by **mutations** in the genes that regulate normal cell division.

Cancer does not only affect humans—it can affect other animals and even plants. All living organisms have cells, so they can all develop cancer, whether they live on land or in water. In fact, many marine (ocean) species develop cancers, such as whales, dolphins, sea lions, walruses, turtles, fish, sponges, and corals. In this article, we focus on a peculiar type of cancer that affects shellfish species.

CONTAGIOUS CANCERS?

Most cancers are not **contagious**, meaning they cannot spread from one person to another like the flu or COVID-19 can. This means that, when a person with cancer dies, the cancer also dies. However, researchers have recently found some types of cancer that can survive even after the organism dies. A type of cancer discovered in certain shellfish called **bivalves** can spread between individuals and is thus known as a contagious cancer. In contagious cancers, cancer cells leave the affected individual, survive in seawater, and infect another individual. These cancers have been found in many bivalve species, including cockles, clams, and mussels.

THE PECULIAR CASE OF CONTAGIOUS CANCER IN BIVALVES

The scientific term for contagious cancers affecting bivalves is disseminated neoplasia. "Neoplasia" means "new growth" and "disseminated" means that the cancer spreads through all organs. In bivalves, the cancer spreads through their **haemolymph**, which is their form of blood. Scientists can remove a drop of haemolymph using a syringe and observe it under a microscope. Cancer cells are easily identifiable because they are larger than healthy cells. Furthermore, as cancer is a disease in which cells divide uncontrollably, it is very common to find cancer cells in the midst of **mitosis** (Figure 1). The rapid division of cancer cells causes the bivalve's organs to deform, which prevents their proper functioning. For example, if the gills no longer have their normal structure, the bivalve will be unable to get oxygen from the water, which can ultimately lead to death.

DNA studies have been important in the discovery that these bivalve cancers are contagious. In an individual with a non-contagious cancer, the DNA of healthy cells is very similar to the DNA of cancer cells. However, in an individual with a contagious cancer, the DNA of cancer cells is quite different from the DNA of healthy cells because

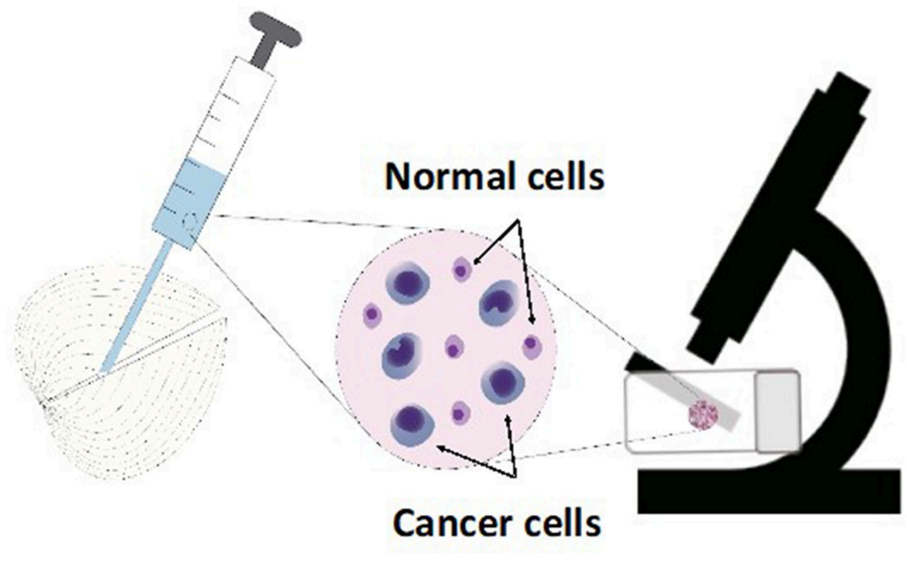


Figure 1

Diagnosis diagram of bivalve cancer in the laboratory. Bivalves with cancer are diagnosed by observing a drop of the haemolymph under a microscope. Cancer cells are larger than healthy cells and are often in the process of mitosis.

those cancer cells originated in a different organism—the one that infected it.

WHICH BIVALVE SPECIES GET CONTAGIOUS CANCERS?

Several contagious cancers have been found in species of clams, cockles, and mussels all over the world (Figure 2). These shellfish live in coastal areas, so they can be easily caught when the tide goes out or by using small boats. The first contagious cancer in bivalves was diagnosed in softshell clams along the Atlantic coast of the United States and Canada [1, 2]. In Europe, contagious cancers have found in clams from the Baltic Sea [3], and in common cockles from the Atlantic coast of Europe [1, 4]. Lastly, two mussel species found worldwide have also been found to be affected by contagious cancers. In fact, contagious cancers in mussels have been detected in locations that are very far from each other, such as the East and West coasts of the United States, Canada, Argentina, Peru, France, Russia, and Japan [5, 6].

SUPER-POWERFUL CONTAGIOUS CANCERS

On rare occasions, contagious cancers can spread to a different bivalve species. This is the case with two contagious cancers detected in clams off the Spanish coast. DNA studies of the contagious cancers detected in warty venus and golden venus clams revealed that these cancers originated in a different clam species [1, 7]. For example, a contagious cancer that originated in striped venus clams was found in warty venus clams (Figure 3). Although researchers have seen several cases of contagious cancers spreading to closely related species,

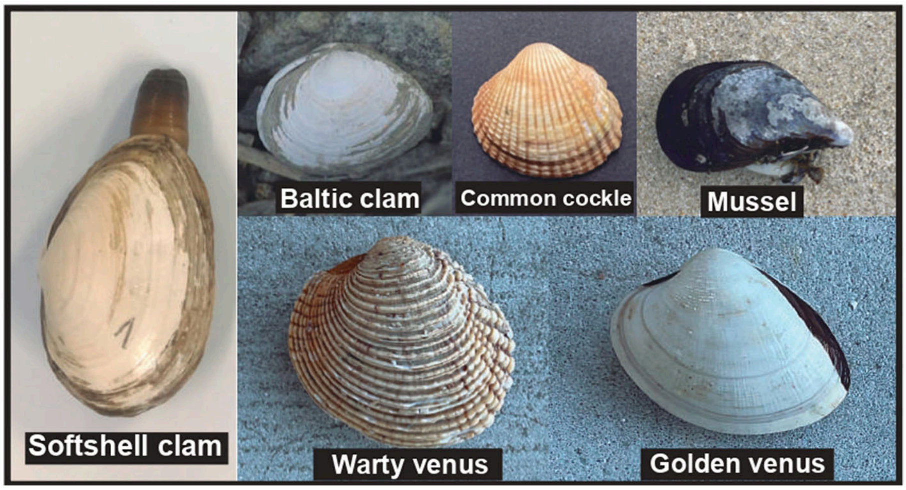


Figure 2

Figure 2

Species of bivalves that are known to be affected by contagious cancers.

contagious cancers do not spread to all the bivalve species that are living close to the infected individuals.

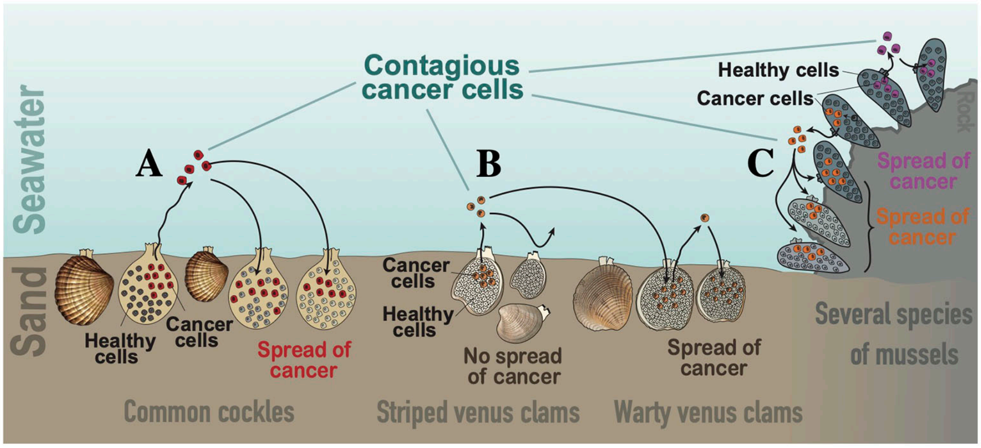


Figure 3

Figure 3

(A) A contagious cancer arises in common cockles and spreads among the population of cockles (same species). **(B)** A contagious cancer arises in striped venus clams and spreads among warty venus clams (a different species). **(C)** Two contagious cancers arise in a mussel species and while one of them (orange) only infects the same species, the other cancer (pink) continues to spread in both that species *and* in other mussel species.

CAN HUMANS GET CANCER FROM EATING SHELLFISH?

Contagious cancers in bivalves are highly specific to those organisms and have only been found to infect closely related species. Not all bivalves living near affected individuals become infected [8]. Thus, it is unlikely that humans could ever become infected with cancer from eating shellfish. When we eat bivalves, our bodies break down the food to extract nutrients and energy—and a contagious cancer cell from a bivalve could not survive that process. Even if a contagious cancer cell could enter the human body, humans have an effective immune system that can defend against many diseases. In a nutshell, it is extremely unlikely that humans could become infected with cancer from shellfish.

WHY ARE MARINE CONTAGIOUS CANCERS IMPORTANT TO STUDY?

Studying marine contagious cancers is important for three main reasons. First, bivalve cancers can be fatal for the affected organisms because cancer cells reach all their organs, preventing them from carrying out their normal functions. Second, contagious cancers have revolutionized our understanding of cancer in marine organisms. We now know that each individual with cancer poses a threat to all healthy individuals, as they can release cancer cells that can survive in the marine environment for days, waiting to infect another organism. In other words, these cancers behave like infectious diseases, such as the flu or COVID-19. Third, understanding why contagious cancers affect many bivalve species could help scientists to understand what makes a cell become cancerous in the first place.

IMPACTS ON BIODIVERSITY

The discovery of contagious cancers puts a new twist on understanding a disease that kills many people each year. Contagious cancers have also been found in species that live on land, including dogs and Tasmanian devils. In the case of Tasmanian devils, contagious cancer is driving the species to extinction, decreasing Earth's **biodiversity**. However, the contagious cancer found in dogs does not kill the animals quickly, so the cancer can survive for years. Studies have found that this contagious dog cancer could be the oldest known cancer. Since it can remain alive after death of the original host, it has been able to survive for thousands of years [9].

BIODIVERSITY

It refers to the rich variety of life on Earth, including different species of plants, animals, and living things in a place.

In summary, we now know that, although it is rare, cancer can be contagious in some cases. Will we find more contagious cancers in nature? This is a question that researchers will try hard to answer in the years ahead.

ACKNOWLEDGMENTS

SD has received funding from the European Union's Horizon 2021 research and innovation programme (HORIZON-MSCA-2021-PF-01) under the Marie Skłodowska-Curie grant agreement No. 101066116.

REFERENCES

1. Metzger, M. J., Villalba, A., Carballal, M. J., Iglesias, D., Sherry, J., Reinisch, C., et al. 2016. Widespread transmission of independent cancer lineages within multiple bivalve species. *Nature* 534:705–9. doi: 10.1038/nature18599

2. Hart, S. F. M., Yonemitsu, M. A., Giersch, R. M., Garrett, F. E. S., Beal, B. F., et al. 2023. Centuries of genome instability and evolution in soft-shell clam, *Mya arenaria*, bivalve transmissible neoplasia. *Nat. Cancer*. doi: 10.1038/s43018-023-00643-7
3. Michnowska, A., Hart, S. F. M., Smolarz, K., Hallmann, A., and Metzger, M. J., 2022. Horizontal transmission of disseminated neoplasia in the widespread clam *Macoma balthica* from the Southern Baltic Sea. *Mol. Ecol.* 31:3128–36. doi: 10.1111/mec.16464
4. Bruzos, A. L., Santamarina, M., García-Souto, D., Díaz, S., Rocha, S., Zamora, J., et al. 2023. Somatic evolution of marine transmissible leukemias in the common cockle, *Cerastoderma edule*. *Nat Cancer.* doi: 10.1038/s43018-023-00641-9
5. Hammel, M., Simon, A., Arbiol, C., Villalba, A., Burioli, E. A. V., Pepin, J. F., et al. 2022. Prevalence and polymorphism of a mussel transmissible cancer in Europe. *Mol. Ecol*. 31:736–51. doi: 10.1111/mec.16052
6. Skazina, M., Odintsova, N., Ivanova, M., Ivanova, A., Vainola, R., and Strelkov, P., 2021. First description of a widespread *Mytilus trossulus*-derived bivalve transmissible cancer lineage in *M. trossulus* itself. *Sci. Rep*. 11:5809. doi: 10.1038/s41598-021-85098-5
7. García-Souto, D., Bruzos, A. L., Díaz, S., Rocha, S., Pequeño-Valtierra, A., and Roman-Lewis, C. F., et al. 2022. Mitochondrial genome sequencing of marine leukemias reveals cancer contagion between clam species in the Seas of Southern Europe. *eLife* 11:e66946. doi: 10.7554/eLife.66946
8. Díaz, S., Villalba, A., Carballal, M. J. 2017. Assessment of transmissibility of the disseminated neoplasia affecting cockles Cerastoderma edule in Galicia (NW Spain). *Bull. Eur. Assoc. Fish Pathol.* 37:5–15.
9. Baez-Ortega, A., Gori, K., Strakova, A., Allen, J. L., Allum, K. M., Bansse-Issa, L., et al. 2019. Somatic evolution and global expansion of an ancient transmissible cancer lineage. *Science* 365:eaau 9923. doi: 10.1126/science.aau9923

SUBMITTED: 17 February 2023; **ACCEPTED:** 07 November 2023;
PUBLISHED ONLINE: 28 November 2023.

EDITOR: Sanae Chiba, North Pacific Marine Science Organization, Canada

SCIENCE MENTORS: Manjusha Verma and Yang Song

CITATION: Bruzos AL and Diaz S (2023) Contagious Cancers That Can Spread Between Ocean Organisms. Front. Young Minds 11:1129218. doi: 10.3389/frym.2023.1129218

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

ARIA, AGE: 11

Aria loves playing with her two guinea pigs and feeding birds and squirrels in her backyard. She gave each squirrel a unique name and lots of peanuts. Aria is always curious about science, and she has a lot of questions about nature, animals, and the universe. She also likes singing and drawing in her spare time.

SIA, AGE: 10

Sia is a vivacious student of class six. She is a good storyteller and wants to be an author among many other things! She loves to read and swim. She engages easily with her peers and seniors and is a very keen observer of her surroundings (a scientist in the making!!).

AUTHORS

ALICIA L. BRUZOS

Alicia L. Bruzos is a cancer researcher at a precision medicine laboratory in London. She has studied human cancers and marine contagious cancers since 2016. Her favorite part of working in science is doing different things every day: traveling to the beach to collect cockles or clams, doing experiments while wearing a fancy lab coat, analyzing data on a supercomputer, teaching genetics to college students and, when she has time, sketching figures. She had already visited as many countries as years old she is (25) and that is why, when she is not working, Alicia is traveling.

SEILA DIAZ

Seila Diaz studied marine science in Vigo (Spain) and completed her doctorate at the University of Santiago de Compostela (Spain). She studies the diseases that affect shellfish, especially cancers. Nowadays she works at the University of Aveiro under a Marie Sklodowska-Curie contract. She loves to find herself in the thousand and one stories in adventure books. She practices marine sports, especially diving. Seila has managed to make her passion since she was a little girl—the sea—into the subject of her day-to-day work. *seila.diaz@ua.pt

frontiers | Frontiers for Young Minds

EARTH SCIENCES
Published: 24 November 2023
doi: 10.3389/frym.2023.1080694

FRESH GROUNDWATER BENEATH OUR OCEANS

Jasper J. L. Hoffmann[1,2] and Aaron Micallef[1,3]*

[1] *Marine Geology and Seafloor Surveying Group, Department of Geosciences, University of Malta, Msida, Malta*

[2] *Coastal Geology, Wadden Sea Station, Alfred-Wegener-Institute, Helmholtz Centre for Polar and Marine Research, List, Germany*

[3] *Monterey Bay Aquarium Research Institute, Moss Landing, CA, United States*

YOUNG REVIEWERS:

ALYSSA
AGE: 12

ANNA
AGE: 12

AURORA
AGE: 11

BRANDON
AGE: 13

LUIZA
AGE: 13

Have you ever tried to dig a deep hole at the beach? At the bottom of the hole, it probably got very wet, making it difficult to dig any deeper. That is when you reached the groundwater. In many places, groundwater is the main source of fresh water for drinking and farming. In your hole on the beach, the water was probably salty and not drinkable right? That is because you are so close to the salty ocean. However, in some locations, you can find freshwater coming out of the ground right on the beach. In other locations, if you swim out into the ocean and dive down, you can find holes in the seafloor where fresh groundwater comes out. These groundwater springs in the ocean are important for the surrounding ecosystems and coastal communities. Fresh groundwater can be found up to 90 km off the coast and could be a potential future source of drinking water in dry regions.

WHAT IS GROUNDWATER?

Groundwater is all the water that exists beneath Earth's surface. On land, groundwater is used by billions of people as a source of fresh drinking water. We also use groundwater to water our plants and grow our food. Groundwater generally forms and renews when it rains or snows, as the water slowly trickles down into the soil. We call this process of water trickling into the ground "recharge" of the groundwater. Actually, 99% of the liquid freshwater on our planet (everything not stored in ice caps and glaciers) is found underground, in the tiny spaces between grains of sand and other sediments [1]. This means that all the freshwater you can see on the surface, for example in rivers or lakes, makes up only 1% of the Earth's liquid freshwater!

Geological formations called **aquifers** store and transport groundwater underneath Earth's surface (Figure 1). Within these aquifers, groundwater slowly flows downwards, generally from the mountains toward the oceans, just like rivers. By drilling wells into aquifers, we can pump groundwater back to the surface and use it for drinking, irrigation, or other purposes. Often, aquifers are blocked at the top and bottom by geological layers that are very dense, like rock or clay, and where the groundwater cannot move through easily. These flow-blocking layers are called **aquitards** (Figure 1).

AQUIFER

An underground layer of porous rock or soil that collects and transports water that people can pump out and use.

AQUITARD

An underground layer of rock or sediment that slows down or permits the flow of groundwater between aquifers above and below it.

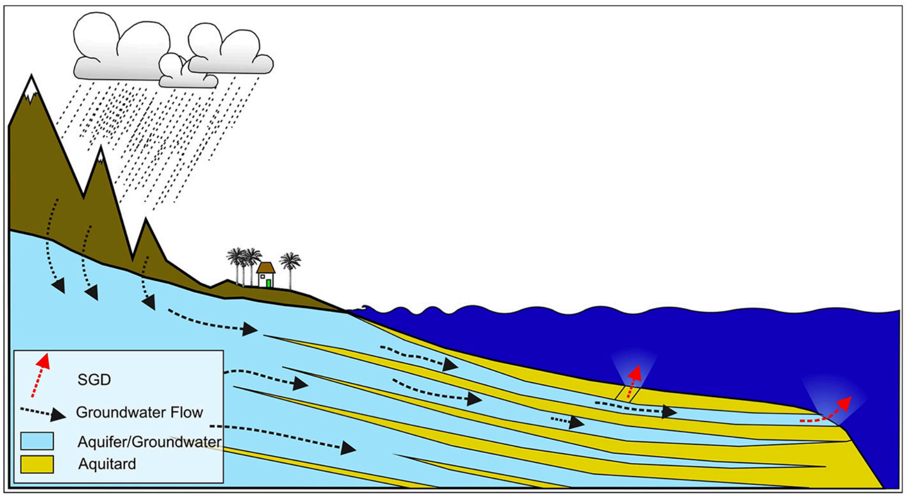


Figure 1

Figure 1

Groundwater forms through rain and snow falling on land and seeping into aquifers. Aquifers then flow "downhill" underground, from the land to the sea. The groundwater is contained in the aquifers by aquitards—layers of rock or other dense material that do not allow water to seep through. Aquifers can continue to carry water beneath the ocean. Red arrows indicate places where fresh groundwater can be released into the ocean by a process called submarine groundwater discharge (SGD).

WHAT IS OFFSHORE FRESHENED GROUNDWATER?

Offshore groundwater describes all the water that is stored in the ground beneath the seafloor. Since the oceans are very salty, the groundwater within the seafloor is generally also salty and cannot be used for drinking or cooking. In some regions though, very large volumes of freshwater can be found beneath the ocean. In fact, these regions can extend up to 90 km off the coast and contain more freshwater than all the water that has ever been removed from aquifers on land [2]. Because the water in these offshore aquifers is sometimes fresh but might be mixed with some saltwater, we call these water bodies offshore freshened groundwater.

WHERE DOES OFFSHORE FRESHENED GROUNDWATER COME FROM?

Groundwater forms when rain and melting snow slowly soaks into the soil and trickles down through the rocks. But no rain or snow falls on the seafloor, right? Rain and snow fall *on top* of the ocean—so how can there be freshwater beneath our salty oceans? Two main processes are responsible for groundwater beneath the seafloor [3].

First, aquifers that are recharged on land can extend beneath the oceans. Often, aquifers are capped at the top and the bottom by aquitards and the water cannot escape. So, when it rains on land and the aquifer fills with water, it will run "downhill" within the aquifer and continue past the coastline, so that the freshwater ends up under the ocean (Figure 1). When a lot of rain falls on land, the pressure in the aquifer builds up. Then the groundwater starts to seep out from the seafloor, like fountains of freshwater under the ocean. We call this submarine groundwater discharge (SGD) (Figure 1). SGD happens in many regions, most of the time relatively close to land, where it often results in holes in the seafloor [4].

A second reason that freshwater can be found beneath the seafloor is that it has been there for thousands of years. During past ice ages, a lot of water was frozen at the North and South Poles. This caused sea levels to drop about 120 m lower than they are today. When the sea level dropped, large areas that are currently covered by the ocean were dry land. During this time, rain was trickling into the ground, building up large volumes of groundwater. By the end of the ice ages, the sea level rose again and these areas became covered with water, as they are today. However, in many places, the groundwater is still there, under the ocean (Figure 2). Since these areas are now covered by seawater, which is slightly heavier than freshwater, the seawater slowly sinks down into the ground, forming salty groundwater beneath the ocean. Eventually, the offshore freshened groundwater will be replaced by seawater.

WHY IS OFFSHORE FRESHENED GROUNDWATER IMPORTANT?

Humans can pollute the groundwater in coastal areas due to farming or release of industrial wastes and sewage. When this groundwater seeps out from aquifers beneath the ocean, it often carries large

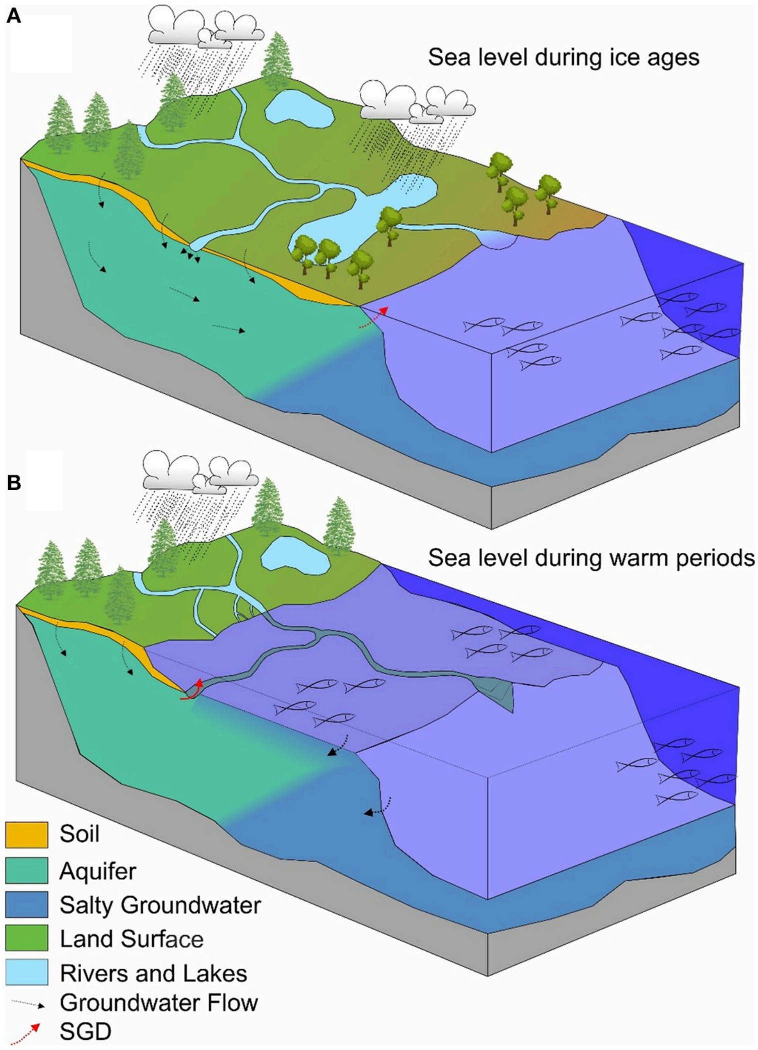


Figure 2

Figure 2

(A) During the ice ages, in the last 100,000 years, sea level was ~120 m lower than it is today, so more land was exposed where rain and snow could seem in to help build up groundwater. **(B)** As the weather warmed and ice melted at the poles, sea levels rose again but the groundwater remained in its place. Red arrows indicate places where fresh groundwater is released into the ocean.

NUTRIENTS

A substance that provides nourishment. Nutrients are contained in food and are essential for life and for the growth of biology.

ALGAL BLOOMS

Dense layers of tiny green plants (algae) that occur on the surface of the ocean when there is an overabundance of nutrients.

amounts of **nutrients** into the ocean water. These nutrients can cause harmful overgrowth of tiny plants called algae. Such **algal blooms** can damage the marine ecosystem. In other areas where groundwater seeps out under the ocean, certain ecosystems thrive because the water is not as salty as the surrounding ocean. Some fish, corals, and plants grow better when the water is less salty and carries more nutrients [5]. So, to protect these environments in the future, it is important to understand where this groundwater discharge occurs, the quality of the groundwater, and how the groundwater affects the surrounding ecosystems.

Freshwater is a valuable resource. In many regions worldwide, people do not have access to fresh, clean drinking water. With the advance of climate change and an increase in droughts, the groundwater in some regions is being increasingly depleted. When the normal water reserves are no longer enough for the coastal population, offshore groundwater might be a unique resource to help with freshwater shortages in some regions [2]. In the future, we could be pumping groundwater from offshore aquifers back onto land, to provide people in coastal areas with enough water to drink and water their plants.

WHERE AND HOW DO WE FIND OFFSHORE GROUNDWATER?

Offshore freshened groundwater has been found along many coastlines around the world (Figure 3). On land, it is relatively easy to drill a groundwater well and to explore aquifers, but it is a lot more complicated and expensive in the ocean. We cannot just use a snorkel and some goggles to dive down to the seafloor and start digging! The freshwater is far too deep under the ground, and the water is much deeper than in swimming pools. Because it is so expensive to drill a well in the ocean, it is very important for us to know exactly where offshore groundwater and SGDs are *before* we try digging. When the groundwater seeps out into the ocean, the freshwater mixes with the saltwater very quickly. That makes it quite difficult to find the regions where SGDs occur.

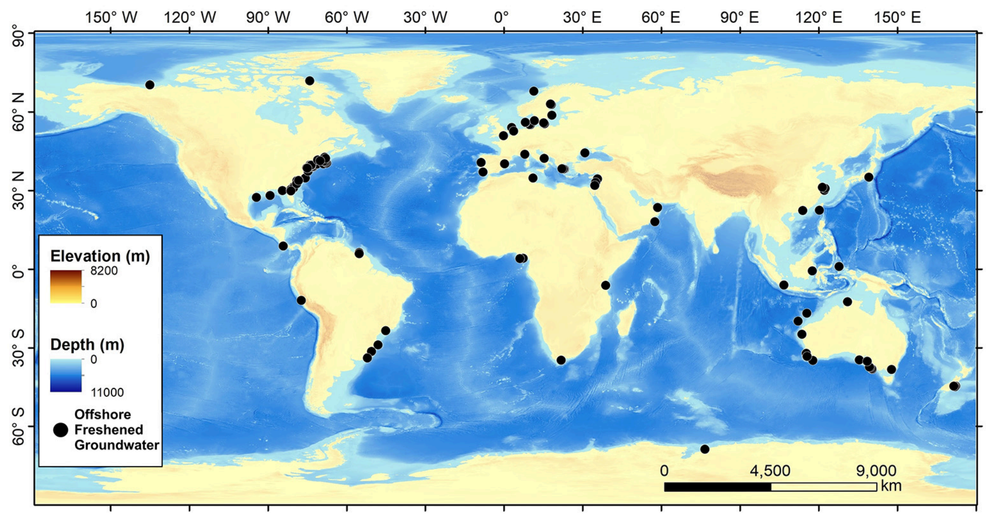


Figure 3

Figure 3

Locations where large quantities of offshore freshened groundwater have been found [figure adapted from [2]].

To find offshore groundwater, we use our research vessels to take special kinds of measurements. One of these methods measures the **electrical conductivity** of the seafloor. We use a battery and a long cable to send electricity into the ground, to see how well the seafloor conducts the electric current. Saltwater is a very good electrical conductor, so the electric current can easily pass through it. Freshwater, on the other hand, cannot conduct electricity very well. Therefore, we look for regions where the seafloor and the ground below show low electrical conductivity. This gives us clues about where we might find offshore freshened groundwater.

ELECTRICAL CONDUCTIVITY

The ability of a material to allow electric currents to pass through it.

We can also look at the properties of water samples that we collect from the ocean. Groundwater can not only carry large amounts of nutrients but can also sometimes have very small amounts of radioactive elements like radon that normally do not occur in the ocean. So, when we find elevated concentrations of radon in our water samples from the ocean, it is likely that groundwater is coming out of the seafloor in these regions.

CONCLUSIONS

It is difficult to find freshwater beneath the ocean, but better techniques are being invented and more and more scientists are searching for these water sources. Several normal Earth processes can generate freshwater beneath the oceans, and a better understanding of these processes could help us to more accurately predict where offshore freshwater might occur and where we should search. The use of offshore freshened groundwater can potentially help us meet our increasing need for freshwater in the future.

ACKNOWLEDGMENTS

This work was funded by the Marie Curie action KARST, under the EU H2020 program, project number 101027303.

REFERENCES

1. Shiklomanov, I. A., Rodda, J. C. 2004. *World Water Resources at the Beginning of the Twenty-First Century*. Cambridge: Cambridge University Press.
2. Micallef, A., Person, M., Berndt, C., Bertoni, C., Cohen, D., Dugan, B., et al. 2021. Offshore freshened groundwater in continental margins. *Rev. Geophys.* 59:1–54. doi: 10.1029/2020RG000706
3. Post, V. E. A., Groen, J., Kooi, H., Person, M., Ge, S., Edmunds, W. M. 2013. offshore fresh groundwater reserves as a global phenomenon. *Nature* 504:71–8. doi: 10.1038/nature12858
4. Hoffmann, J. J. L., Mountjoy, J. J., Spain, E., Gall, M., Tait, L. W., Ladroit, Y., et al. 2023. Fresh submarine groundwater discharge offshore Wellington (New Zealand): hydroacoustic characteristics and its influence on seafloor geomorphology. *Front. Mar. Sci.* 10:1204182. doi: 10.3389/fmars.2023.1204182
5. Lubarsky, K. A., Silbiger, N. J., Donahue, M. J. 2018. Effects of submarine groundwater discharge on coral accretion and bioerosion on two shallow reef flats. *Limnol. Oceanogr.* 63:1660–76. doi: 10.1002/lno.10799

SUBMITTED: 26 October 2022; **ACCEPTED:** 06 November 2023;
PUBLISHED ONLINE: 24 November 2023.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Josephine Jayworth and Bibiana Monson De Souza

CITATION: Hoffmann JJL and Micallef A (2023) Fresh Groundwater Beneath Our Oceans. Front. Young Minds 11:1080694. doi: 10.3389/frym.2023.1080694

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

ALYSSA, AGE: 12

I am Alyssa, in my free time I enjoy going to my local library and checking out books. It is exciting picking what will be my next reading adventure; whether it is fiction, science, or about history. I love reading books about science theories the most because they talk about the many possibilities in the universe.

ANNA, AGE: 12

I am Anna and I am a Swimmer who likes to engage in any fun physical activities. I love art specifically painting. I am a girl scout and boy scout. I love to go camping with my troop and go on hikes. I also love to engage in sciences. I love chemistry because I love to watch how the reactions happen and learn why it happens. Although I love to do activities, I love to sit on the computer and make videos and watch.

AURORA, AGE: 11

I am Aurora, I really love science. We have biology classes at school, but I really want to explore and learn more about chemistry.

BRANDON, AGE: 13

I am Brandon, I am in 8th grade and the types of science I am interested in are biological science, physical science, and social science.

LUIZA, AGE: 13

I am 13 years old, I really like to write. I am passionate about adventures, suspense and magic. I like to go out with my friends and family. I am very interested in biology, as I am the daughter of biologists. Since I was a little girl, I have had contact with many animals and I love catching cockroaches and other arthropods in my hand. When I grow up I will be a comic artist, I love to draw.

AUTHORS

JASPER J. L. HOFFMANN

I am a marine geophysicist, which means I investigate the seafloor and everything that lies underneath it. I completed my Ph.D. at the University of Otago in New Zealand and my research now focuses on groundwater occurrences and discharge under the ocean. In my free time, I enjoy swimming in the ocean, windsurfing, hiking, and playing football with my friends. *jasper.hoffmann@um.edu.mt

AARON MICALLEF

I am a marine geologist with an interest in exploring the seafloor to better understand the hazards and resources that it hosts. I received my Ph.D. from the University of Southampton in the UK. My pastimes include hiking, running, and reading.

EARTH SCIENCES
Published: 06 October 2023
doi: 10.3389/frym.2023.943491

KEEPING AN EYE ON EARTH'S OCEANS WITH ARGO ROBOTS

***Blair J. Greenan*[1*]*, Annie P. Wong*[2]*, Tammy Morris*[3]*, Emily A. Smith*[4] *and Marine Bollard*[5]

[1] *Bedford Institute of Oceanography, Fisheries and Oceans Canada, Halifax, NS, Canada*
[2] *School of Oceanography, University of Washington, Seattle, WA, United States*
[3] *South African Weather Service, Cape Town, South Africa*
[4] *National Oceanic and Atmospheric Administration (NOAA), Washington, DC, United States*
[5] *Euro-Argo European Research Infrastructure Consortium (ERIC), Brest, France*

YOUNG REVIEWERS:


DENIZ
AGE: 12


LEO
AGE: 12


OMER
AGE: 14

Have you ever wondered how scientists know what is happening deep below the surface of the ocean? There are several types of robots that can dive below the sea surface and bring back data from underwater. One type of robot, called an Argo float, moves through the middle depths of the ocean with the currents and comes to the surface once every 10 days, to tell scientists about the information that it has collected. Currently, there are about 4,000 Argo robots keeping an eye on Earth's oceans every day. These robots measure ocean temperature and saltiness, and some can also monitor more complex chemical and biological parameters. Argo robots provide another tool in an oceanographer's toolbox, to help scientists understand how the ocean works and how it impacts not only marine life, but also the whole Earth.

WHY ARE SCIENTISTS KEEPING AN EYE ON EARTH'S OCEANS?

The ocean is very important to human wellbeing because it provides us with food, medicines, transportation, and recreation. The ocean is also home to many marine (ocean) species that make Earth friendly to humans. For example, the small **plankton** in the ocean produce more than 50% of the oxygen that we breathe. The ocean makes up more than 70% of Earth's surface area and plays a major role in the planet's environment. For all these reasons, scientists have known for many years that it is essential to observe the ocean, to better understand it and to predict the changes that may happen.

PLANKTON

Drifting plants, algae, and some bacteria that can photosynthesize.

Scientists who study the atmosphere are also interested in observations of the ocean because the weather we experience every day is influenced by the ocean. For example, have you ever seen water evaporating from a hot road? The same thing happens in the ocean, when warm sea surface temperatures cause evaporation, which transfers water from the ocean to the atmosphere. Once in the atmosphere, the water helps to form clouds, snow, and rain. So, better monitoring of ocean conditions results in better weather forecasts.

Some scientists are specialists in studying Earth's **climate**. Regions with a "tropical climate" get a lot of sunlight each year. That makes the sea surface warm and produces clouds and rain, so the climate in these regions is typically hot and humid. But the climate can change over time. For example, some human activities, such as driving cars or heating our homes, can add **greenhouse gasses** to the atmosphere. Greenhouse gasses act like a blanket, trapping heat and warming Earth's surface. Ocean observations are important for understanding how greenhouse gasses are contributing to climate change because the ocean can absorb carbon dioxide and heat from Earth's atmosphere and move them around via ocean currents.

CLIMATE

The description of the long-term pattern of weather in a particular area. This is typically estimated as an average of the data collected (for example, temperature) over at least two decades.

GREENHOUSE GASSES

Gases that trap heat in the atmosphere including carbon dioxide, methane, nitrous oxide and fluorinated gases.

ARGO ROBOTS: FREE-ROAMING OCEAN ADVENTURERS!

To study the ocean, scientists must consistently collect data for many years. One important way to get this information is to go on ships to take measurements (See also this Frontiers for Young Minds article). But there are places that are difficult for ships to get to, such as the Arctic and the Antarctic. Winters also produce rough seas that are difficult for ships to operate in. To collect measurements from Earth's oceans in all seasons, scientists invented Argo robots (Figure 1).

These Argo robots are called "floats," and they carry **sensors** to collect ocean data. Even though we call these robots "floats," they actually go up and down in the ocean. Scientists put Argo robots

SENSORS

A device that detects and responds to some type of input from the physical environment.

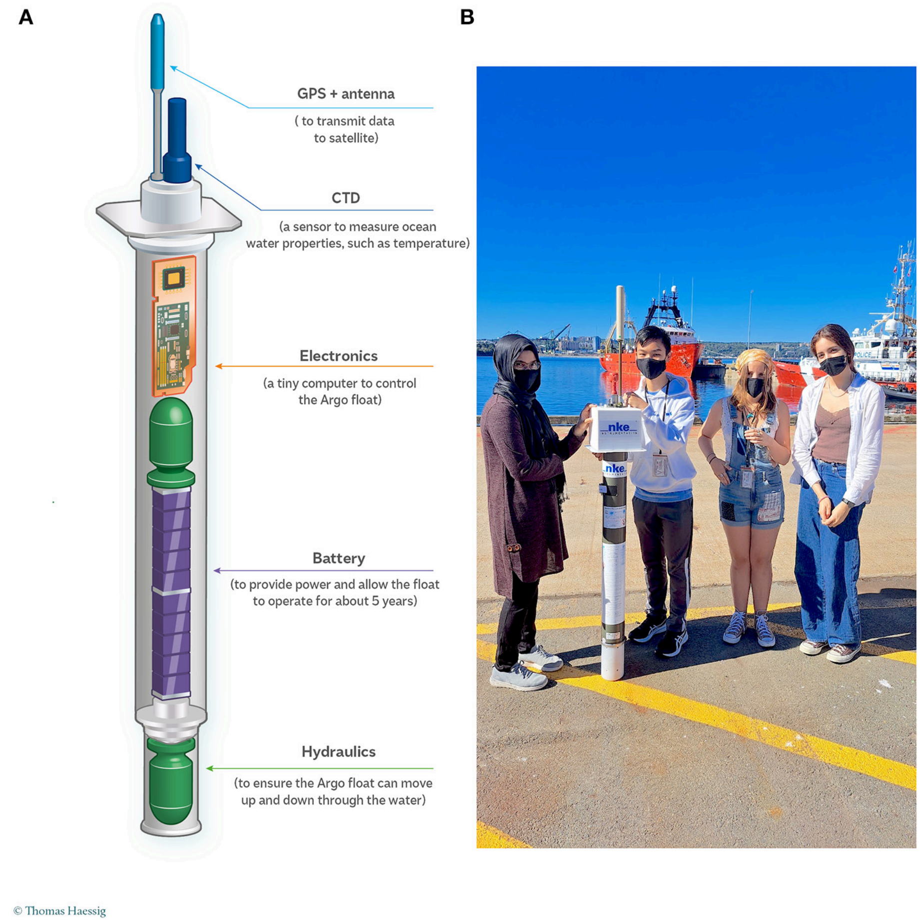


Figure 1

Figure 1

(A) A drawing showing the main components of an Argo robot (Image credit: © Thomas Haessig). **(B)** A group of high school students with an Argo robot. These students were participating in the development of the Adopt-a-float program in Canada.

into the ocean from ships. Once they are in the ocean, they sink to 1,000 m and move freely with the ocean currents at that depth for 9 days. On the 10th day, they dive to 2,000 m, then rise to the surface, taking ocean measurements on their way up. When they reach the surface, they send the data they collected and their location back to the scientists via satellites, thus enabling scientists to build a database of information about this part of the ocean. After that, they dive back to 1,000 m and start the cycle over again (Figure 2A). Scientists use computer programs to check the measurement quality and transfer the information to a database (Figure 2B). The measurements are freely available to everyone within 24 h of the robots surfacing (Figure 2C).

Argo robots record pressure, temperature and **salinity** measurements. Salinity is a measure of the concentration of salt in the ocean. Salinity and temperature together determine the **density** of seawater. Pressure tells the scientists the depth at which the temperature and salinity measurements are taken. In the ocean, one meter (m) in depth is about the same as one decibar (dbar) in pressure. In the atmosphere, high and low pressures create our weather systems. In the ocean, high and low density areas create currents, which move large amounts of

SALINITY

A measure of the concentration of salt in the ocean. This can also be referred to as saltiness.

DENSITY

The amount of matter in a substance (its mass) divided by how much space the substance takes up (its volume).

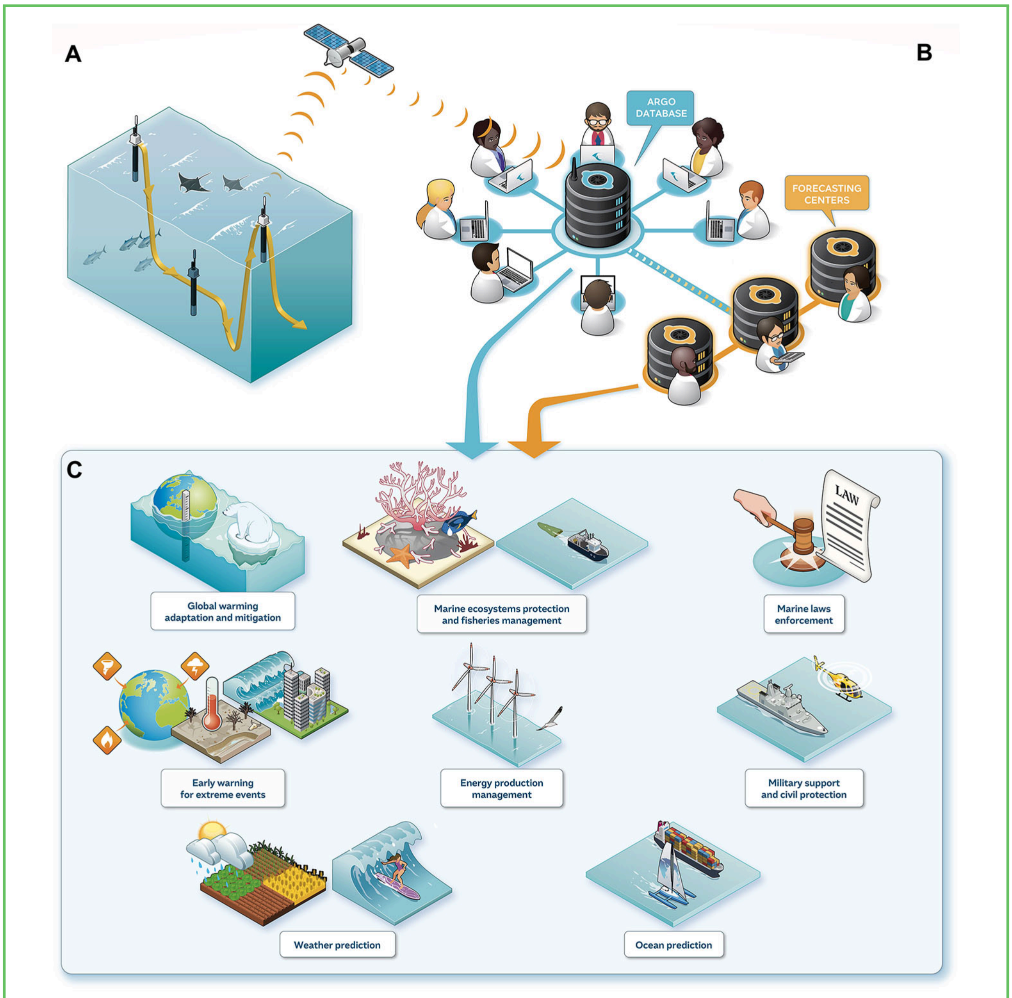


Figure 2

Figure 2

(A) An Argo float drifts with ocean currents 1,000 m below the surface. Every 10 days it sinks to 2,000 m and then rises to the surface, collecting ocean data on its way up. At the surface, it connects to a satellite and sends the information it has collected to science teams around the world. **(B)** The information is stored in a database for everyone to use, and it helps to improve local weather forecasts. **(C)** There are many applications of Argo data that improve our daily lives (Figure credit: © Thomas Haessig).

water around the globe. Understanding how water moves around in the ocean is important for research on climate, as well as for protecting the plants and animals that live in the ocean.

When scientists first designed the network of Argo robots in the late 1990s, they wanted the data to complement sea surface height measurements collected by a satellite named *Jason*. In Greek mythology, Jason sailed on a ship named *Argo*, searching for the golden fleece. Therefore, the ocean scientists called these robots Argo floats. Sea surface height data from satellites can be combined with Argo data to inform scientists about changes in ocean currents. The Argo robots have been roaming the ocean for the past 20 years and have collected over 2 million measurements around the world [1]. Today there are almost 4,000 Argo robots collecting ocean measurements.

Argo robots are powered by batteries and work around the clock every day of the year. Because of these robots, scientists can now keep an eye on Earth's oceans like never before. The batteries in Argo robots usually last more than five years. When the batteries are used up, these robots will become inactive and sink to the ocean bottom. While this may seem like littering the ocean, the environmental impact on the ocean is extremely small compared to other pollutants, and the ocean data collected is extremely valuable for understanding Earth.

WHAT CAN ARGO ROBOTS TELL US ABOUT THE OCEAN?

Since 1970, the ocean has taken up more than 90% of the heat created by greenhouse gasses from human activities. Temperatures in many areas of the world's oceans have increased. One way that scientists monitor this is by using temperature and salinity measurements to calculate how much heat has been added to a layer of the ocean, called **ocean heat content** (Figure 3). By using data collected by Argo robots, scientists have discovered that extreme events like heat waves are occurring more often in the ocean, just as they are in the atmosphere. These marine heat waves cause marine animals to move to other areas to find cooler water. However, plants and animals that cannot move will suffer from these marine heatwaves.

OCEAN HEAT CONTENT

The amount of energy in the form of heat that is stored in the ocean.

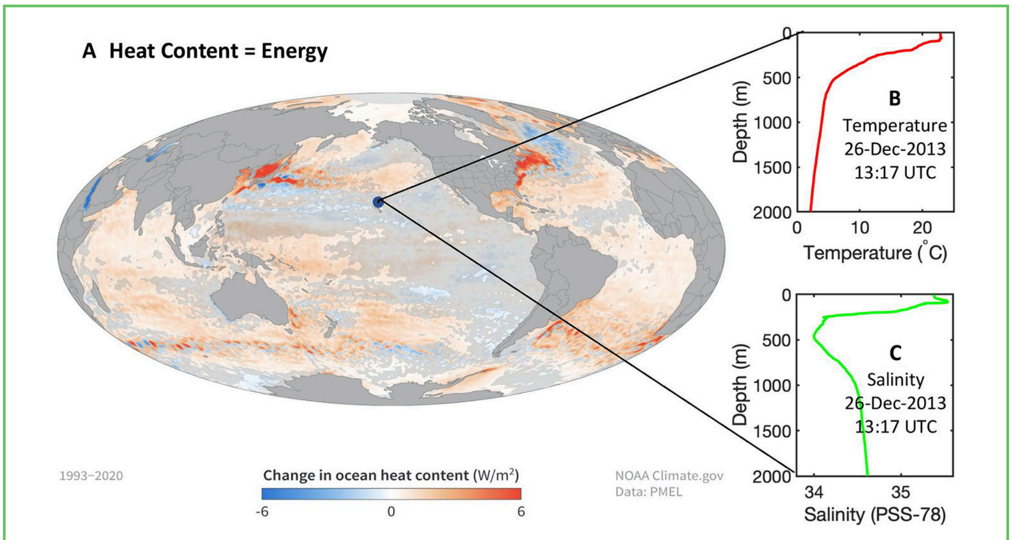


Figure 3

(A) Change in ocean heat content in the upper 700 m of the ocean from 1993–2020. Heat content is a measure of energy and is calculated from temperature and salinity. Between 1993–2019, ocean heat content rose by up to 6 Watts per square meter in parts of the ocean (dark red). Some areas lost heat (blue), but overall, the ocean gained more heat than it lost. **(B)** Example temperature and **(C)** salinity measurements from an Argo robot near Hawaii, reported on December 26, 2013.

Global sea level rise is another big consequence of climate change. As the water in the ocean warms, it also expands, which is one of the main causes of sea level rise. A rising sea level can have dramatic impacts in our daily lives because it can cause flooding, erosion, and make freshwater undrinkable due to mixing with salty seawater (See this Frontiers for Young Minds article for more information on sea level rise). Argo robots are a key tool in monitoring global sea level rise because they keep an eye on how Earth's oceans are changing.

Keeping track of the ocean has also led to improvements in weather forecasting. Using the temperature and salinity data sent back by Argo

COMPUTER MODEL

A program that runs on a computer to simulate a real-world system such as Earth's atmosphere or oceans.

robots, scientists have added a **computer model** of the ocean to their weather forecast calculations. Having real ocean data in these models improves scientists' understanding of how the atmosphere and the ocean interact with one another. This is very important for predicting intense storms like hurricanes, cyclones, and typhoons, which gain a lot of their strength from warm ocean surfaces.

GOING DEEPER AND IN NEW DIRECTIONS

In the past, Argo robots were restricted to the top 2,000 m of the ocean, which represents <50% of the global ocean volume. It is very challenging to design robots that can travel to the bottom of the ocean, but scientists and engineers have recently succeeded in making some robots that can dive as deep as 6,000 m [2]. Sampling the ocean from the surface to the bottom will enable scientists to better understand changes in heat and freshwater content, and this will provide better information about global sea level rise.

We are now at the dawn of a new era, in which Argo robots can make measurements related to ocean chemistry and biology [3]. This will provide information on changes in the amounts of oxygen and carbon dioxide in the ocean, for example. The global ocean is currently losing oxygen and absorbing more carbon dioxide from Earth's atmosphere. These changes are having impacts on the marine ecosystems, including the fisheries that feed many of us.

Argo robots are one tool in an oceanographer's toolbox. They are part of a global system called the Global Ocean Observing System (GOOS). Together with other partners in GOOS, the advances in Argo robots will help us build a global picture of ocean health and how it is changing over time. You too can join these ocean observers. How? By adopting a float. You can choose an Argo robot, give it a name, and follow its journey around the world. You can also learn more about Argo at the Argo Online School and at Ocean Observers. An ocean adventure awaits!

SOURCE ARTICLE

Wong, A. P. S., Wijffels, S. E., Riser, S. C., Pouliquen, S., Hosoda, S., Roemmich, D. et al. 2020. Argo data 1999–2019: two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling Floats. *Front. Mar. Sci.* 7:700. doi: 10.3389/fmars.2020.00700

REFERENCES

1. Wong, A. P. S., Wijffels, S. E., Riser, S. C., Pouliquen, S., Hosoda, S., Roemmich, D. et al. 2020. Argo data 1999–2019: two million temperature-salinity profiles and

subsurface velocity observations from a global array of profiling floats. *Front. Mar. Sci.* 7:700. doi: 10.3389/fmars.2020.00700

2. Roemmich, D., Alford, M. H., Claustre, H., Johnson, K., King, B., Moum, J. et al. 2019. On the future of argo: a global, full-depth, multi-disciplinary array. *Front. Mar. Sci.* 6:439. doi: 10.3389/fmars.2019.00439
3. Bittig, H. C., Maurer, T. L., Plant, J. N., Schmechtig, C., Wong, A. P. S., Claustre, H., et al. 2019: A BGC-argo guide: planning, deployment, data handling and usage. *Front. Mar. Sci.* 6:502. doi: 10.3389/fmars.2019.00502

SUBMITTED: 13 May 2022; **ACCEPTED:** 21 September 2023;
PUBLISHED ONLINE: 06 October 2023.

EDITOR: Pedro Morais, Florida International University, United States

SCIENCE MENTORS: Laura Lorenzoni and Sagi Dalyot

CITATION: Greenan BJ, Wong AP, Morris T, Smith EA and Bollard M (2023) Keeping an Eye on Earth's Oceans With Argo Robots Front. Young Minds 11:943491. doi: 10.3389/frym.2023.943491

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

DENIZ, AGE: 12

Hi, my name is Deniz and I like to watch the stars and play video games with friends. My favorite star cluster is Messier 45 and my favorite constellation is Orion belt. My favorite video game is Call of Duty 2.

LEO, AGE: 12

Leo was born in Florida and likes the beach; he especially enjoys snorkeling. He likes history and mythology, especially if underwater. He plays the cello and has two dogs, and enjoys playing videogames in his spare time.

OMER, AGE: 14

I am interested in international politics, and I like to read about politics, philosophy, and history. I like to play video games on my Nintendo switch and pc, and I love to listen to music and play roleplaying games as D&D and Warhammer 40K.

AUTHORS

BLAIR J. GREENAN

Blair Greenan is a research scientist at the Bedford Institute of Oceanography based in Halifax, Nova Scotia, Canada. He manages the Canadian contribution to the international Argo program. His research focuses on helping coastal communities adapt to ocean climate change. This includes addressing infrastructure issues by providing science-based tools with information on local changes in sea level resulting from climate change. *Blair.Greenan@dfo-mpo.gc.ca

ANNIE P. WONG

Annie is a research scientist at the University of Washington in Seattle, WA, United States. She is an oceanographer who started in marine science collecting ocean data from ships. She now uses Argo data to study ocean salinity and is interested in the oceans around Antarctica. She is part of the Argo Data Management Team that helps distribute Argo data to the public.

TAMMY MORRIS

Tammy Morris is a senior scientist within the Marine Unit of the South African Weather Service based in Cape Town, South Africa. She is an observational oceanographer having spent many months at sea on research vessels working with ocean-observing instruments such as Argo floats, drifters, and moorings. Her research has concentrated around the greater Agulhas Current system, and more recently interactions with the Southern Ocean.

EMILY A. SMITH

Emily is the manager of several programs including the U.S. Argo Program, the Global Sea Level Observing System (GLOSS), ocean gliders in boundary currents, and ocean heat content products. Emily is responsible for managing budgets and strategic planning for the observing systems. She also coordinates the Adopt a Drifter program, which facilitates partnerships with schools in the U.S. and abroad, so they can track drifting buoys and use the data in real time in their classrooms. Before coming to NOAA, Emily spent several years teaching middle school students, and this program helps keep her connected to the education world.

MARINE BOLLARD

Marine is responsible for the outreach activities of the Euro-Argo European Research Infrastructure Consortium (ERIC). ERIC is dedicated to the development of a long-term European contribution to the Argo global ocean monitoring system, with the aim to support better understanding and prediction of the ocean, its role in the climate system, and ocean health. She holds two master's degrees in hydrogeology engineering and science journalism. Before coming to Euro-Argo, Marine spent several years publishing science popularization books and articles for educational purposes and the public.

frontiers | Frontiers for Young Minds

BIODIVERSITY
Published: 06 September 2023
doi: 10.3389/frym.2023.972231

HOW ARE DEEP-SEA ANIMALS GETTING INTO SEDIMENT TRAPS IN ANTARCTICA?

Minkyoung Kim[1,2*], Eun Jin Yang[3], Hyung Jeek Kim[4,5], Dongseon Kim[4], Tae-Wan Kim[3], Hyoung Sul La[3], SangHoon Lee[3] and Jeomshik Hwang[2]

[1] *Department of Oceanography, Kyungpook National University, Daegu, Republic of Korea*

[2] *School of Earth and Environmental Sciences, Research Institute of Oceanography, Seoul National University, Seoul, Republic of Korea*

[3] *Division of Ocean Sciences, Korea Polar Research Institute, Incheon, Republic of Korea*

[4] *Deep-sea Mineral Resources Research Center, Korea Institute of Ocean Science & Technology, Busan, Republic of Korea*

[5] *Tropical and Subtropical Research Center, Korea Institute of Ocean Science & Technology, Jeju, Republic of Korea*

YOUNG REVIEWERS:


JULIA
AGE: 11


MUHAMMAD
AGE: 13


THEO
AGE: 12

A sediment trap is a tool to collect small, sinking particles in the sea. Unexpectedly, we found deep-sea animals inside four traps placed in the Amundsen Sea, Antarctica. The animals were long, slim worms, sea urchins, and baby scallops. These animals do not swim, so how did they enter the traps? As this surprising finding happened mostly during winter, we think that ice may have helped them get into the traps. If enough of a certain kind of ice, called anchor ice, forms on an animal's body, it can make the animal float. If the animal floats up to the sea ice on the ocean's surface, it can attach and be transported as the ice moves around. When the anchor ice melts the animals are released, and they enter our traps as they sink to the ocean bottom. Future research is needed to know for sure if this is how the animals entered our traps!

WHAT ARE SEDIMENT TRAPS?

The Amundsen Sea, one of the major seas surrounding Antarctica, is experiencing serious melting of glaciers and **sea ice** due to global warming. As the sea ice melts, small ponds open in the Amundsen Sea for 2–3 months during the summer. This area of open water is called a **polynya** (Figure 1a). When the polynya opens in summer, the region becomes like a green soup, crowded with many organisms that make a lot of carbon-containing particles that sink to the seafloor (Figure 1b). This process by which organisms, especially phytoplankton make carbon-containing particles by using the oxygen and sunlight is called, "primary production". These particles are the main sources of sinking particles. In addition to that, sinking particles are usually combinations of dead organisms, feces (poop), resuspended sediment, dust, and other similar substances. Most particles are very small (smaller than 1 mm). Together, these tiny particles are called **particulate organic carbon** (POC). Particulate organic carbon sinks into the deep ocean and finally ends up in the **sediments**, which are deposits on the floor of the ocean **sediment traps** are widely used to collect sinking particles in the oceans (Figures 2a, b). We attached sediment traps to a line and threw the line into the Amundsen Sea—the traps float underwater, but the weighted lines anchor them in place. Slowly sinking particles are captured inside the sediment traps. After 1–2 years, we revisited the sites and recovered the sediment traps in summer, when the sea ice is melted and it is easier to visit the Antarctic. In this study, our traps were positioned at four locations with different sea-surface conditions: a sea ice-covered area (Station K1), the central Amundsen Sea Polynya (Station K2), near the Dotson Ice Shelf (Station K3), and near the East Getz Ice Shelf (Station K4) (Figure 1a).

SEA ICE

Frozen seawater that floats on the ocean, especially in the Arctic and Antarctic. Sea ice can move by the winds and currents.

POLYNYA

Polynya is an area of water surrounded by sea ice or land. Polynyas can be sustained by winds or ocean heat.

PARTICULATE ORGANIC CARBON

Tiny particles made by marine organisms in the ocean's surface water, such as feces (poop) or dead organisms. These particles slowly sink down into the deep ocean.

SEDIMENTS

All kinds of particles sink and settle on the seafloor. This includes sinking particles made by marine organisms in the ocean's surface water and small parts of rock or sand.

SEDIMENT TRAP

An ice cream cone-shaped device to collect particles sinking to the bottom of the deep ocean.

A COLLECTION OF MYSTERIOUS WORMS

Unexpectedly, at three locations (K1, K3, and K4), deep-sea animals were found in the sediment traps, including long, slender worms, sea urchins, and baby scallops of varying sizes (Figures 2c–e). This was the first reported collection of these deep-sea animals in sediment traps. In the laboratory, we counted the number of animals, including entire bodies and body parts. The lengths and thicknesses of the worms were measured using a ruler and Vernier calipers. The worms were similar in appearance (Figure 2e) and had a rubbery texture. The bodies were round, slender, and <5 mm thick. Five worms were dried, weighed, and finely ground to analyze the carbon content in their bodies.

At Station K3, a total of 33 worms were collected from April–August and in December 2012, and 24 worms were collected in July 2013 alone. Two worms were collected at station K1 in June 2012 and early March 2013. The worms collected at stations K1 and K3 varied in length from 2 to 69 cm (Figure 2e). At Station K4, we found 11 baby scallops,

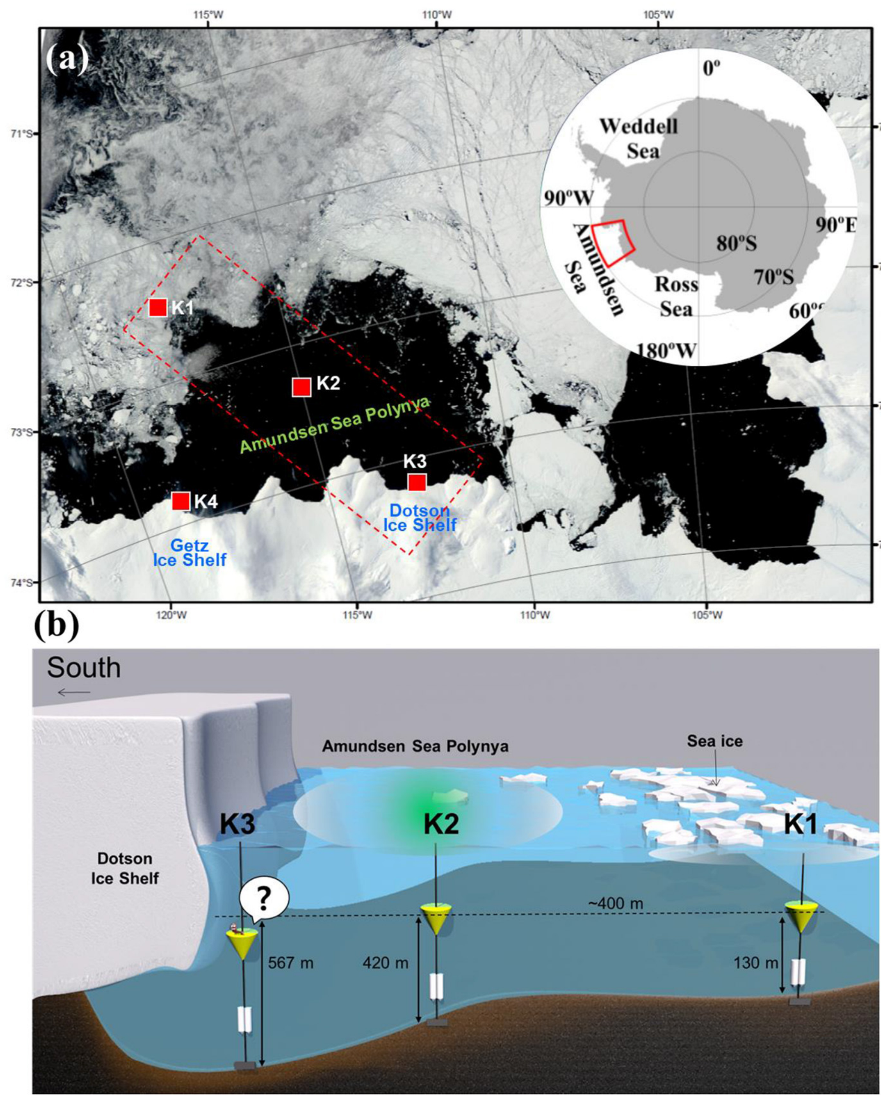


Figure 1

Figure 1

(a) Locations of sediment traps (red squares) in the Amundsen Sea. The satellite image shows the sea ice on February 15, 2012. The black areas in the image are open water (Amundsen Sea polynya) and the white regions are covered by sea ice. **(b)** Showing the locations and depths of the sediment traps in the Amundsen Sea (figure modified from [1]).

1 baby sea urchin, and 12 worms (including seven incomplete bodies). Worms were found between March and September 2016 and from June to July 2017. One scallop was collected from August–September 2017, and 10 from October–November 2017. The scallops were babies and varied in size from 1.2 to 2.8 cm. One baby sea urchin was collected between October and November 2017. No specimens were collected when there was not any sea ice present.

HOW DID THESE ANIMALS GET INTO THE SEDIMENT TRAPS?

The lid of the sediment trap, consisting of mesh with holes about 2.5 cm in diameter would have prevented any larger creatures larger than that diameter from falling into the trap. So, it is puzzling that deep-sea animals that cannot swim were collected in sediment traps

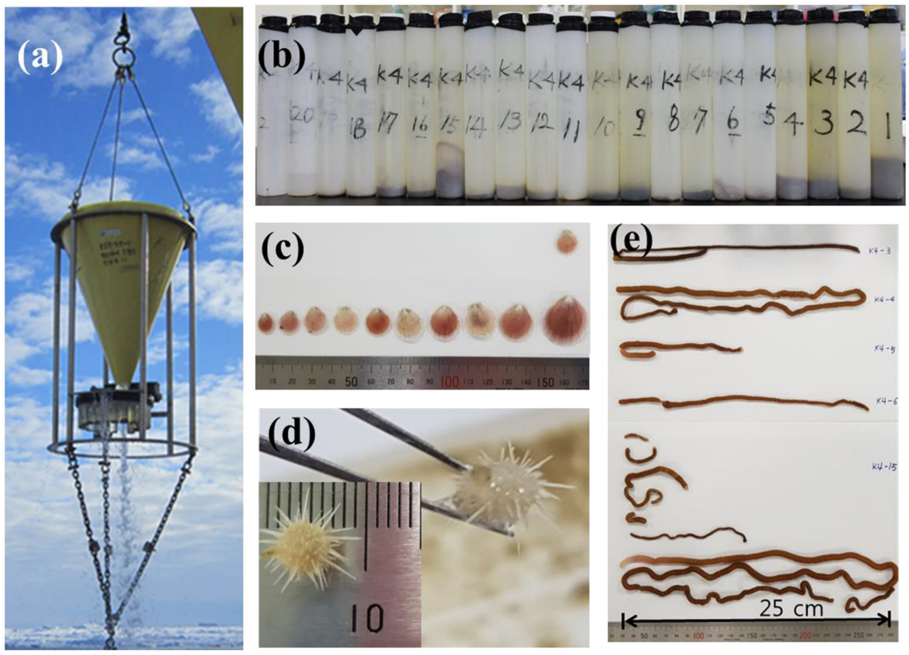


Figure 2

(a) One of the sediment traps we used in the Amundsen Sea. **(b)** Bottles containing the worms found in trap K4. **(c)** Baby scallops, **(d)** a sea urchin, and **(e)** worms collected at Station K4.

130–567 m above the seafloor. It is unlikely that these animals crawled up the mooring lines and jumped into the traps! Strong ocean currents may have carried these animals to trap sites. Small, light, baby scallops might be particularly affected by strong currents. However, the current was not particularly strong at the time the animals were collected. We think it is possible that the animals were transported in, and released from, sea ice. **Anchor ice**, which forms in **supercooled** water [2], may have gently trapped these animals. Like the "anchor", anchor ice is the attached ice to the bottom. Ocean animals living in the seafloor can be captured by the anchor ice when it forms. Any anchor ice formed on deep-sea animals' bodies would cause them to float, lifting them to the sea ice floating on the ocean surface. The animals could then stick to the sea ice via the anchor ice on their bodies [2]. The sea ice with attached animals moves around following the surface water current. When the attached anchor ice melts, the animals are released from the sea ice and drift back down toward the bottom. In the process, some of them may have been caught in our sediment traps.

ANCHOR ICE

A type of ice that forms usually when the water is supercooled. The ice crystals in the water attach to marine organisms or sediments, like the anchor.

SUPERCOOLED

In cold polar waters, sometimes the water is not frozen even though temperatures drop below the freezing point. This process is called supercooling.

ANCHOR ICE IN THE AMUNDSEN SEA?

Studies on anchor ice formation have focused mainly on the Arctic, where anchor ice is the main way that sediment ends up in sea ice and is transported to new areas [3]. In the Antarctic, anchor ice has been reported at several locations, such as the McMurdo Sound in the Ross Sea [2]. Although supercooling may happen in the Amundsen Sea, it has not been reported because no data from this area are available except from the summer, when anchor ice would not form anyway.

However, strong winds, freezing temperatures, and strong turbulence in an open, shallow sea all occur in the Amundsen Sea in winter, and those are the necessary conditions for anchor ice formation [4]. Future research is needed to verify that anchor ice forms in the Amundsen Sea, as such data would support our hypothesis.

WHAT DID WE LEARN AND WHY IS IT IMPORTANT?

The lifting of deep-sea animals to the sea surface by ice is thought to be important for the ocean food web. The role of anchor ice in carrying deep-sea animals far away from the coast has not yet been investigated in Antarctica. The amount of carbon contained within these organisms is about five times larger than the amount of carbon found in the average concentration of particulate organic carbon in ocean water, so these lifted animals may provide energy for other ocean animals during the winter, particularly when there is not enough food. If deep-sea animals can survive being trapped in anchor ice that is attached to the sea ice, this process may serve as a way for animals to spread to distant areas. We have no evidence of whether the animals entered our sediment traps alive or dead, so more research is needed in this area. Overall, this article taught us the impact of anchor ice on Antarctic biology. This information is important for understanding not only the existence and formation of anchor ice in the Amundsen Sea, Antarctica but its role to supply the energy and food to the deep-sea.

ACKNOWLEDGMENTS

The original work has been supported by the Korea Institute of Ocean Science and Technology (grant no. PN67330), the Korea Polar Research Institute (grant no. PE18060), and the National Research Foundation of Korea (global PhD fellowship no. 2015032018). The original study made use of rapid response imagery from the Land, Atmosphere Near real-time Capability for EOS (LANCE) system, operated by the NASA's GSFC Earth Science Data and Information System (ESDIS), with funding provided by NASA/HQ.

ORIGINAL SOURCE ARTICLE

Kim, M., Yang, E. J., Kim, H. J., Kim, D., Kim, T.-W., La, H. S., Lee, S., and Hwang, J. 2019. Collection of large benthic invertebrates in sediment traps in the Amundsen Sea, Antarctica, *Biogeosciences* 16:2683–91. doi: 10.5194/bg-16-2683-2019

REFERENCES

1. Kim, M. 2019. *Present and Past Organic Carbon Cycling on the Amundsen Shelf, Antarctica: Implications from Radiocarbon and Sterols, Doctoral Dissertation.* Seoul: Seoul National University
2. Dayton, P. K., Robilliard, G. A., and Devries A. L. 1969. Anchor ice formation in McMurdo Sound, Antarctica, and its biological effects, *Science* 163:273–4. doi: 10.1126/science.163.3864.273
3. Nürnberg, D., Wollenburg, I., Dethleff, D., Eicken, H., Kassens, H., Letzig, T., et al. 1994. Sediments in Arctic sea ice: implications for entrainment, transport and release. *Mar. Geol,* 119:185–214. doi: 10.1016/0025-3227(94)90181-3
4. Reimnitz, E., Marincovich, L., McCormick, M., and Briggs W. 1992. Suspension freezing of bottom sediment and biota in the Northwest Passage and implications for Arctic Ocean sedimentation. *Can. J. Earth Sci.* 29:693–703. doi: 10.1139/e92-060

SUBMITTED: 18 August 2022; **ACCEPTED:** 11 August 2023;
PUBLISHED ONLINE: 06 September 2023.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Dalaq Aiysha and Janet Striuli

CITATION: Kim M, Yang EJ, Kim HJ, Kim D, Kim T-W, La HS, Lee S and Hwang J (2023) How Are Deep-Sea Animals Getting Into Sediment Traps in Antarctica? Front. Young Minds 11:972231. doi: 10.3389/frym.2023.972231

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

JULIA, AGE: 11

Julia is a 6th grader student. She is passionate about music and science. Julia plays the drums, the piano, and the bass. She plays in the orchestra and in the jazz band and recently she and her band wrote a song. Julia loves science class and would like to become an F1 engineer.

MUHAMMAD, AGE: 13

The turning point in my curiosity came when I secured first place in my grade 3 Science project. It was about photosynthesis, which I chose after knowing the fact that plants are universal food makers. The Science textbook of every grade always familiarized me about the magical wonders behind my daily life's surroundings.

THEO, AGE: 12

Theo is a 6th grader. His favorite class is science and he would like to be a photographer for National Geographic. Theo plays in a band with his friends and they recently wrote a song. Theo has played a variety of sports and basketball is his favorite.

AUTHORS

MINKYOUNG KIM

I am Minkyoung Kim, assistant professor at Kyungpook National University. As an early career scientist, I am exploring all around the world including the Antarctic and Arctic! My research interest is oceanic carbon cycling. You can find more information about me from my homepage (https://mini3248.wixsite.com/minkyoungkim). *minkyoung@knu.ac.kr

EUN JIN YANG

My name is Eun-Jin Yang. I am the head of Division of Ocean Science in Korea Polar Research Institute. My background is biological oceanography, particularly polar biology. I have been studying the Arctic Ocean and Antarctic Ocean since 2010 using the Ice breaker research vessel "ARAON".

HYUNG JEEK KIM

I work as a principal research scientist at the Korea Institute of Ocean Science and Technology (KIOST). My research interest is climate change and its impact on the marine environment and ecosystem.

DONGSEON KIM

I am a senior researcher working at the Korean Institution of Ocean Science and Technology. My major is a marine biogeochemistry, especially seawater carbonate chemistry. I am now working on ocean acidification, sea-air CO_2 flux, and particle fluxes in the Arctic Ocean and Korean marginal seas.

TAE-WAN KIM

As a principal research scientist at the Korea Polar Research Institute, I am primarily focused on investigating the circulation patterns of seawater in the Southern Ocean. Specifically, I am dedicated to studying the movement of warm seawater and its influence on melting ice shelves.

HYOUNG SUL LA

I am a principal research scientist at the Korea Polar Research Institute and an associate professor at University of Science and Technology. My research focuses on the ecology of polar marine life such as zooplankton, fish, and marine mammals, addressing how environmental changes affect their behavior and distribution in polar marine ecosystem.

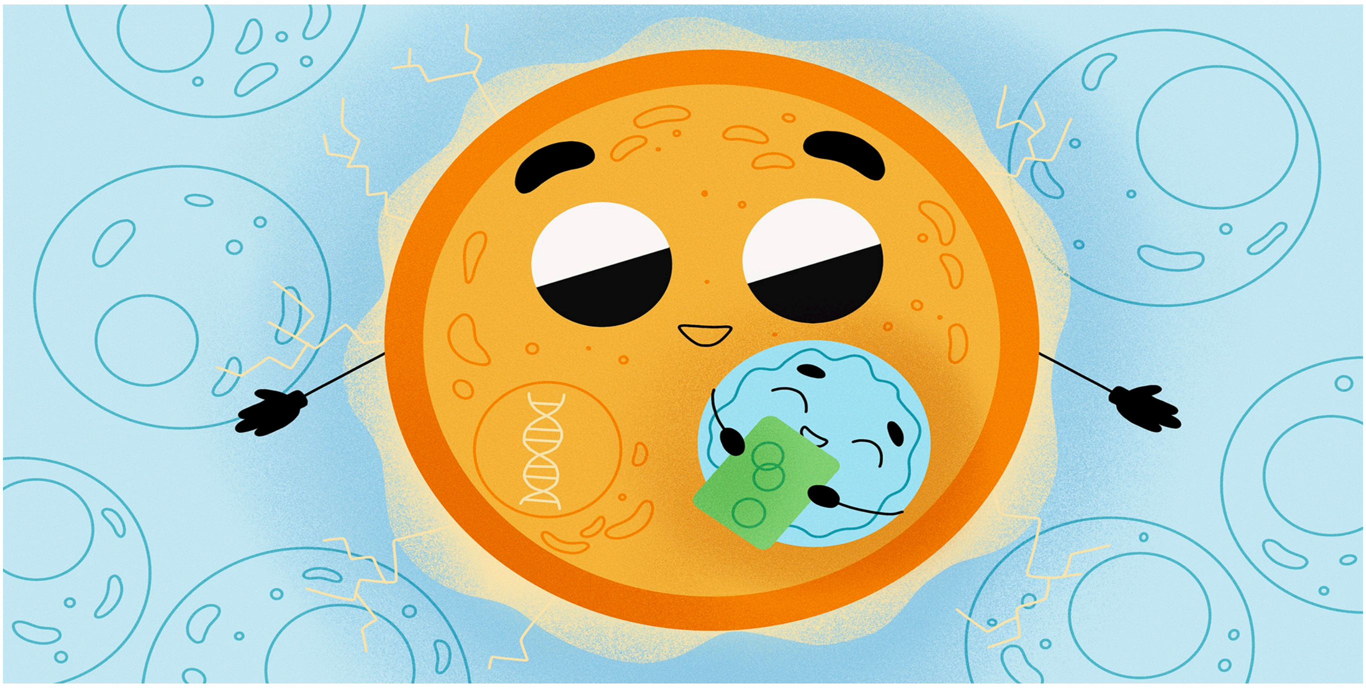
SANGHOON LEE

I was a chief scientist during the Amundsen Cruise. During the cruise, we investigated the animals in sediment traps. As a principal research scientist at the Korea Polar Research Institute, my research interest is microbial ecology.

JEOMSHIK HWANG

I am a professor at Seoul National University. My research interests are processes organic carbon undergoes in the ocean and the impact of climate change on marine biological carbon pump.

BIODIVERSITY
Published: 05 September 2023
doi: 10.3389/frym.2023.1010245



IN OCEANS, LAKES AND PONDS, LIVING THINGS CAN BECOME WHAT THEY EAT

Zachary J. F. Fedder and David R. Smith*

Department of Biology, University of Western Ontario, London, ON, Canada

YOUNG REVIEWERS:

GIACOMO
AGE: 13

GIUSEPPE
AGE: 11

TAPPAN MIDDLE
AGES: 12–13

Most of the world's rich variety of life, called biodiversity, cannot be seen by the naked eye. But just because it is small does not mean it is boring or unimportant! Tiny organisms known as microbes, which are often made up of only a single cell, have many impressive abilities and weird qualities. A lot of the microbial diversity we observe today was made possible by the sharing of DNA between different species through a process called endosymbiosis—in which one organism (the endosymbiont) becomes trapped inside another (called the host). Indeed, an ancient endosymbiotic event resulted in the chloroplasts that trees and green algae use to convert sunlight into energy, for example. Chloroplasts were then passed along, like Pokémon cards, to other organisms through more recent endosymbiotic events, causing an explosion of photosynthesis across the microbial world.

MICROBES RULE THE WORLD

There are millions of species on Earth, most of which are microbes and cannot be seen by the naked eye. All of this diversity comes in two main flavors: prokaryotes and eukaryotes (Figure 1). Animals, plants, and fungi, for example, are **eukaryotes**, which means their cells contain sub-parts known as organelles. Organelles are surrounded by membranes (barriers that let only certain things in and out) and they perform specific tasks that keep cells alive and running. Organelles set eukaryotes apart from "simpler" cells known as prokaryotes. Whereas, eukaryotes can be made of one cell or many cells, prokaryotes are almost exclusively one-celled (unicellular) organisms. Bacteria are classic examples of prokaryotes. Another key difference between eukaryotes and prokaryotes is that eukaryotes have an organelle called the nucleus, which encloses their DNA, whereas prokaryotes do not have a nucleus, meaning their DNA is more "free floating" inside the cell. Through a microscope, eukaryotic cells are generally much larger and more complex than prokaryotic cells (Figure 1).

EUKARYOTES

Organisms with complex cell(s) that contain organelles with membranes, a nucleus to hold DNA, and other intricate characteristics.

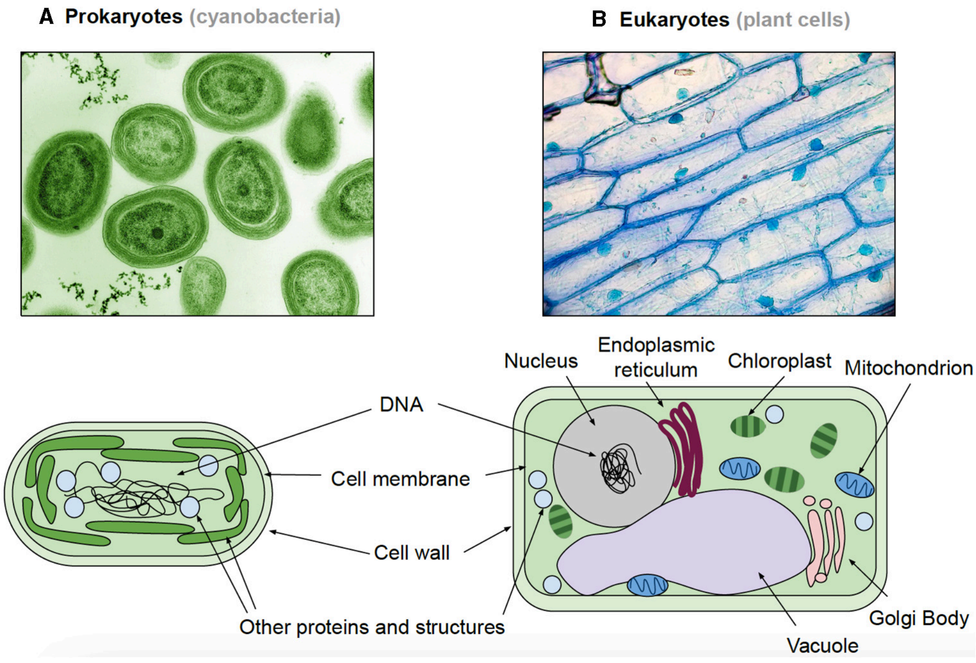


Figure 1

Figure 1

(A) Prokaryotes, like cyanobacteria, are generally smaller and less complex than eukaryotic cells. They do not have a nucleus enclosing their DNA. **(B)** Eukaryotes, like these plant cells (stained blue), have various membrane-bound structures called organelles that perform important functions inside the cell. They contain a nucleus where the DNA is kept. Eukaryotic cells are typically around 100 times bigger than prokaryotic cells—about the size difference between a grain of rice and a beach ball (Photo credits: Wikipedia Commons).

There are millions of eukaryotic species on Earth [1], and most of them are not animals or plants—they are microbes. Much of this microscopic **biodiversity** exists because eukaryotic microbes love eating each other. And in the case of microbes, sometimes you really are what you eat!

BIODIVERSITY

The variety of living things in the world or in a certain area.

In this article, we focus on **plastids**—a type of organelle found in some eukaryotic cells. Plastids produce and store chemicals required for survival. The chloroplasts found in plants and algae are a kind of plastid that converts sunlight into sugar to be used as energy,

PLASTID

A type of organelle that evolved from an endosymbiont. Plastids produce essential chemicals (such as sugars) used by the cell for energy.

a process known as photosynthesis. Plastids are also responsible for much of the biodiversity seen on Earth today, especially among eukaryotic microbes.

BEFORE PLANTS AND ANIMALS

Long ago, before animals and plants existed, microbes dominated Earth's oceans, lakes and ponds (Figure 2A). This was the case for most of Earth's history. Much like animals today, eukaryotic microbes needed to eat to gain energy for survival. No eukaryote could use sunlight to produce its own energy—only some bacteria, including a type called cyanobacteria (Figure 1A), could perform photosynthesis.

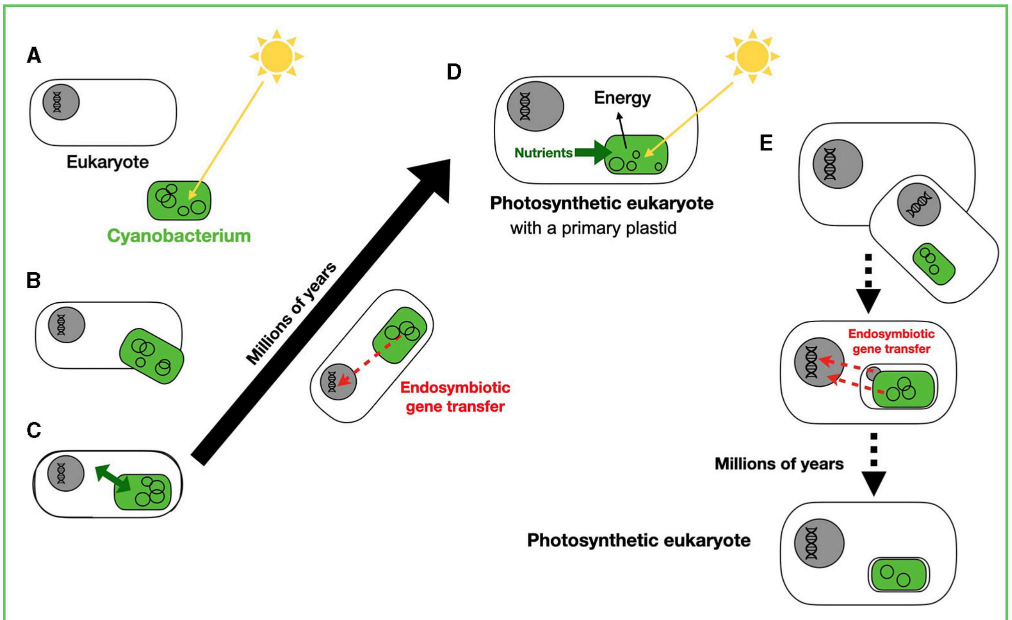


Figure 2

Figure 2

(A) A eukaryote and a cyanobacterium living independently billions of years ago. Cyanobacteria convert sunlight into energy using photosynthesis. **(B)** A eukaryote engulfs a cyanobacterium. **(C)** Primary endosymbiosis, in which the bacterium receives protection and nutrients in return for providing energy from photosynthesis. Over millions of years, endosymbiotic gene transfer (and gene loss) causes the transfer of endosymbiont genes to the host's genome. **(D)** The endosymbiont is eventually an organelle—a primary plastid. **(E)** Higher-order endosymbiosis involves a eukaryote without a plastid engulfing another eukaryote with a primary plastid, in this case a chloroplast that can perform photosynthesis.

More than a billion years ago, a eukaryote engulfed a photosynthetic cyanobacterium (Figure 2B) [2]. Usually, this is no big deal—many eukaryotes hunt and engulf their prey, digest it, extract nutrients, and go on with their day. But not this time! For various reasons, this particular cyanobacterium was not digested. In fact, over time it continued to live inside the eukaryote. This type of relationship is called endosymbiosis because one organism (called the **endosymbiont**) lives inside another (called the host) and can result in each one benefiting from the other. In this case, the eukaryote protected and fed the cyanobacterium and, in return, the cyanobacterium provided the eukaryote with energy produced via photosynthesis (Figure 2C). As the host reproduced (dividing into new cells), the endosymbiont remained inside the host and divided too. All the cells that were descendants of the host contained an endosymbiont that produced energy for them. Eventually, over millions of years, the descendants of this cyanobacterium slowly lost all independence and gradually

ENDOSYMBIONT

An organism that lives inside another organism, often involving the trading of resources.

changed from an endosymbiont (a separate organism) to just another part of the eukaryotic cell—an organelle we now call a plastid (Figure 2D).

This event is known as **primary endosymbiosis** because it involved a prokaryote (the cyanobacterium) and gave rise to a **primary plastid**. Scientists believe mitochondria evolved by a similar process, where an ancestor of eukaryotes engulfed a bacterium, which eventually became the organelle we call a mitochondrion. However, this mitochondria primary endosymbiosis happened much longer ago than plastid primary endosymbiosis. Three main groups of life arose from this primary plastid endosymbiotic event: red algae, green algae plus land plants, and a group of freshwater algae called glaucophytes (Figures 3A–F) [2, 3]. Organisms in these three groups all contain a primary plastid. In other words, without primary endosymbiosis, plants and algae would not exist!

PRIMARY ENDOSYMBIOSIS

The initial event more than a billion years ago when a prokaryote known as a cyanobacterium was engulfed by a eukaryote and eventually became an organelle known as a plastid.

PRIMARY PLASTID

A plastid that evolved from primary endosymbiosis.

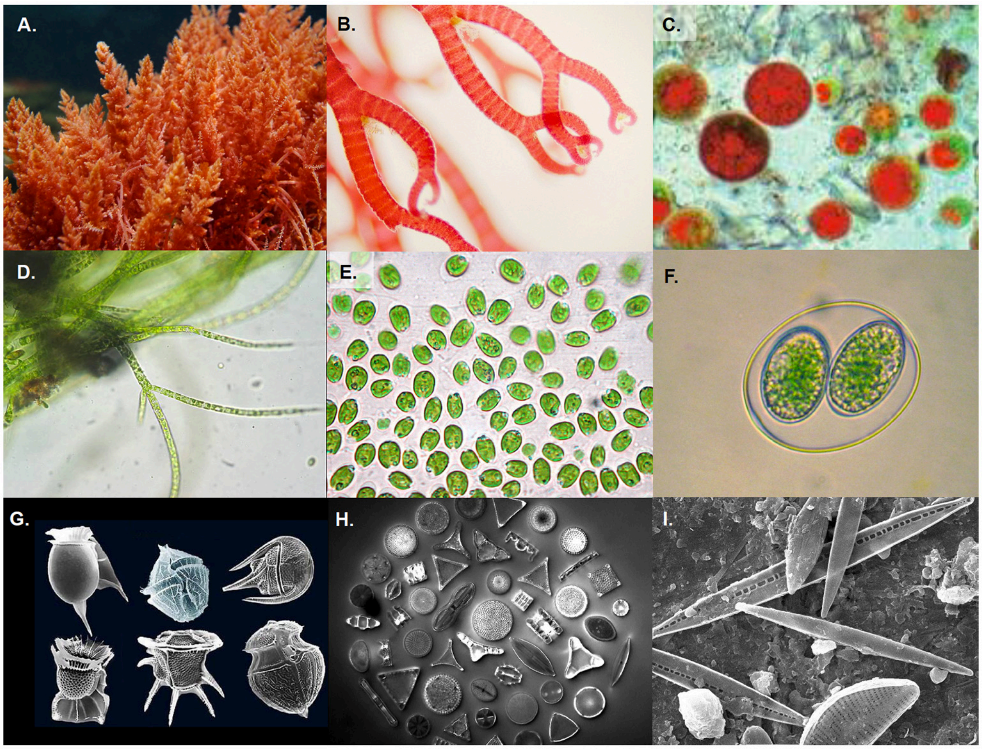


Figure 3

Figure 3

(A–C) Examples of multicellular and unicellular red algae (Photo credits: Encyclopædia Britannica; Wikipedia Commons; Instruments Direct Services Limited). **(D, E)** Examples of multicellular and unicellular green algae (Photo credit: Encyclopædia Britannica; Stevens Point Department of Biology, University of Wisconsin). **(F)** A glaucophyte, freshwater algae with primary plastids (Photo credit: Wikipedia Commons). **(G)** Dinoflagellates seen through an electron microscope (Photo credit: Flickr). **(H, I)** Diatoms seen through an electron microscope (Photo credit: Randolph Femmer, USGS Library of Images From Life; Wikipedia Commons).

NO EUKARYOTE IS SAFE

Plastid endosymbiosis can also occur between eukaryotes. For example, red and green algae which contain plastids, are often gobbled up as food by other kinds of eukaryotes. So—you guessed it—certain red and green algae have evolved (via endosymbiosis) from being food to actual working chloroplasts housed inside of other diverse organisms.

HIGHER-ORDER PLASTID ENDOSYMBIOSIS

Endosymbiosis involving eukaryotes, where one eukaryote becomes the plastid of another eukaryote.

This process is known as **higher-order plastid endosymbiosis** (Figure 2E). When eukaryotes ultimately become plastids in another eukaryote, these plastids are known as complex plastids. One of the main features of complex plastids is that they have more than two membranes, unlike primary plastids. But the most important takeaway is that higher-order endosymbiosis has allowed photosynthesis to spread across the eukaryotic Tree of Life into some really interesting organisms, ones that you would not necessarily think have plastids [3] (Figure 3).

YOU ARE WHAT YOU ENGULF

ENDOSYMBIOTIC GENE TRANSFER

When genes from an endosymbiont are transferred to the host's own genome.

Among the many benefits of endosymbiosis can be the reciprocal exchange of energy and nutrients between the host and the endosymbiont. But this close relationship can also end up mixing the DNA of both organisms, in a process known as **endosymbiotic gene transfer** [4]. Simply put, this involves the movement of the endosymbiont's DNA to the host's genome, much like transferring information from an external drive to a desktop computer.

Endosymbiotic gene transfer is perhaps the key ingredient in the journey from endosymbiont to organelle, as it allows the host to gain more and more control over its cellular resident. Another important ingredient is the outright loss of genes from the endosymbiont, causing it to become more and more dependent on the host. All of this gene blending and gene loss can sometimes lead to very unusual genetic features. Some diatom algae, for example, have special plastids that allow them to produce chemicals that help them survive in even the harshest conditions, like in the Antarctic Ocean where the water is very poor in iron (an essential ingredient for most microbial life) [5].

EVEN MORE DIVERSITY!

Not all plastid endosymbiotic events are successful, and sometimes it takes a few tries to get it right [3, 6]. This means that some algae bear the marks of older higher-order plastid endosymbioses that were either halted before completion or were successful but the plastid was ultimately lost. Think of it like installing a solar panel on a house and the workmen stop the job before completion or the panel gets blown away during a storm. Whatever the outcome, the house will often contain the "scars" of the initial installation in the form of marks on the roof, etc. It is similar with the genomes of certain eukarytoes in that they contain pieces of DNA from old plastid endosymbiotic events [6].

The genomes of some diatom algae (Figure 3) can be a great example of this, containing a random mash-up of dozens of DNA pieces from numerous organisms. Imagine trying to make sushi with a recipe that contains instructions for pasta sauce and tacos! But for diatoms, this mash-up works like a charm. In fact, diatoms are among the most abundant and diverse groups of algae on Earth [6]. Some believe that hundreds, or even thousands of new genes and gene combinations have evolved from the blending of genomes, resulting from endosymbioses, paving the way for new abilities and new species adapted for living in even the harshest environments.

We could go on for another hundred pages describing the many amazing features and outcomes of plastid endosymbiosis. There are millions of species of eukaryotic microbes, each one with unique characteristics and tangled evolutionary histories. In summary, not only is endosymbiosis a fascinating biological process, but without it much of the massive biodiversity we see today would not exist.

REFERENCES

1. Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B., and Worm, B. 2011. How many species are there on earth and in the ocean? *PLoS Biol*. 9:e1001127. doi: 10.1371/journal.pbio.1001127
2. Burki, F., Roger, A. J., Brown, M. W., and Simpson, A. G. B. 2019. The new tree of eukaryotes. *Trends Ecol. Evol*. 35:43–55. doi: 10.1016/j.tree.2019.08.008
3. Sibbald, S. J., and Archibald, J. M. 2020. Genomic insights into plastid evolution. *Genome Biol. Evol.* 12:978–90. doi: 10.1093/gbe/evaa096
4. Timmis, J. N., Ayliffe, M. A., Huang, C. Y., and Martin, W. 2004. Endosymbiotic gene transfer: organelle genomes forge eukaryotic chromosomes. *Nat. Rev. Genet.* 5:123–35. doi: 10.1038/nrg1271
5. Bowler, C., Vardi, A., and Allen, A. E. 2010. Oceanic and biogeochemical insights from diatom genomes. *Annu. Rev. Mar. Sci.* 2:333–65. doi: 10.1146/annurev-marine-120308-081051
6. Dorrell, R. G., and Bowler, C. 2017. "Secondary plastids of stramenopiles," in *Secondary Endosymbioses. Advances in Botanical Research, Vol 84*, ed Y. Hirakawa (London: Academic Press), 57–93.

SUBMITTED: 15 November 2022; **ACCEPTED:** 03 August 2023;
PUBLISHED ONLINE: 05 September 2023.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Francesco Catania and Pamela T. Wong

CITATION: Fedder ZJF and Smith DR (2023) In Oceans, Lakes And Ponds, Living Things Can Become What They Eat. Front. Young Minds 11:1010245. doi: 10.3389/frym.2023.1010245

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

GIACOMO, AGE: 13

My name is Giacomo, and I am 13. I am studying to get into a music school and play guitar, I hang out with friends, I read a lot, I watch TV series and I like to sleep very much.

GIUSEPPE, AGE: 11

My name is Giuseppe and I am 11. I am a video game champion, I like reading comic books, I like drawing, I play soccer and I am also very good at other sports, I am also into Marvel and Star Wars, and I would like to jump between buildings and save the city from criminals.

TAPPAN MIDDLE, AGES: 12–13

This article was reviewed by Charlotte, Evelyn, Louis, and Will, a small group of cheery and bright seventh graders in Ms. Frantom's science class at Tappan Middle School in Ann Arbor, Michigan, USA. Tappan students in sixth through eighth grade achieve at high levels under the facilitation of skilled, effective, culturally competent educators. We completed this review with the help of our UofM mentor, Dr. Pamela Wong.

AUTHORS

ZACHARY J. F. FEDDER

Zachary Fedder completed his undergraduate degree in the Biology Department at Western University. He studied genetics and biochemistry. *zac.fedder@gmail.com

DAVID R. SMITH

David Smith is a professor in the Biology Department at Western University. He studies genome evolution in green algae.

EARTH SCIENCES
Published: 29 August 2023
doi: 10.3389/frym.2023.996462

POO IS PRECIOUS

John J. Kilbane II[1*], Hynek Roubik[2], Andras J. Kovacs[3], Taobat Keshinro[4*], Maulik Patel[5] and Jacob de Feijter[6]

[1] *Department of Biological, Chemical and Physical Sciences, Illinois Institute of Technology, Chicago, IL, United States*
[2] *Department of Sustainable Technologies, Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, Prague, Czechia*
[3] *KUKK K&F Ltd., Budapest, Hungary*
[4] *Department of Microbiology, Rhodes University, Grahamstown, South Africa*
[5] *United States Department of Agriculture, Peoria, IL, United States*
[6] *Te Wananga o Aotearoa, Auckland, New Zealand*

YOUNG REVIEWERS:

JOSEPHINE
AGE: 12

TANISHKA
AGE: 14

Human poo contains precious nutrients, but we flush it down the drain to become wastewater. Wastewater often pollutes rivers, lakes, or the ocean. The high levels of nutrients in wastewater, primarily from human poo and pee, can decrease the amount of oxygen in the ocean, killing the fish that we eat along with other organisms. In the old days, poo from humans and animals was used on farms, as fertilizer. But this is not a practical option for the large volumes of wastewater produced in cities. What if the nutrients from wastewater could be used to solve rather than to create environmental problems? Using single-celled, water-dwelling plants called microalgae to treat wastewater has many benefits. Clean water helps everyone. Recycling nutrients from wastewater and using them as fertilizers will help farmers. Also, useful products like fuels and plastics can

be made from these algae. New and cheaper wastewater treatment technologies are needed to create a better future. You could be part of the solution!

WASTEWATER TREATMENT CHALLENGES

In developed areas of the world, each person produces about 150 l of **wastewater** per day. That is about 50,000 l (12,500 gallons) per person per year, or about 10 million cubic meters for a city of 100,000 people. We use water to flush the toilet, wash our dishes, or have a shower. Normally we do not think about what happens to the water when it goes down the drainpipe—out of sight is out of mind! To avoid damaging the environment, wastewater must be treated before it is released into oceans, lakes, and rivers. Most wastewater worldwide is *not* treated, and even treated wastewater can still contain **pollutants**. The scale of the wastewater problem is enormous, and it gets worse each day as the world's population grows. Industrial wastewater is also a concern, because water coming from manufacturing can be contaminated with dangerous chemicals and heavy metals.

WASTEWATER

Water containing pollutants such as human poo and any water that goes down the drain is called wastewater.

POLLUTANTS

Pollutants are unwanted materials found in wastewater like poo, toxic chemicals, and nutrients like nitrogen and phosphorus.

Wastewater treatment plants do a good job of removing most contaminants, but nutrients like phosphorus and nitrogen are not removed. You might wonder why nutrients can be bad, but nutrient pollution can damage oceans, lakes, and rivers. How? The nutrients released into the environment cause lots of **microalgae** to grow in the waterways where wastewater is released. Microalgae are tiny, single-celled plants and, like all plants, they use sunlight to perform photosynthesis and *produce* oxygen. However, when these large masses of algae die, the bacteria that break them down *use up* lots of oxygen. This can lead to vast regions of the world's oceans that have too little oxygen (Figure 1). These areas are called low-oxygen zones, and they can be deadly to the fish and shellfish we eat, along with many other organisms [1]. When some species of algae grow excessively, they can also produce certain chemicals that are toxic to humans and animals.

WASTEWATER TREATMENT PLANTS

Facilities that are designed to remove pollutants from wastewater are called wastewater treatment plants.

MICROALGAE

Microalgae are single cell plants that grow in water using sunlight and/or pollutants.

But what if microalgae could be part of the solution instead of the problem? Specifically, what if these organisms could be used to *improve* wastewater treatment? First, we will tell you about how wastewater is commonly treated, and then we will explain how microalgae can help!

WASTEWATER TREATMENT OVERVIEW

Treatment of wastewater is essential to avoid pollution of lakes, oceans, and rivers (Figure 2). The first step of treatment is screening. Screening removes large particles such as wood, grease, rags, plastic, and gravel. Then comes the removal of smaller, dense particles. This

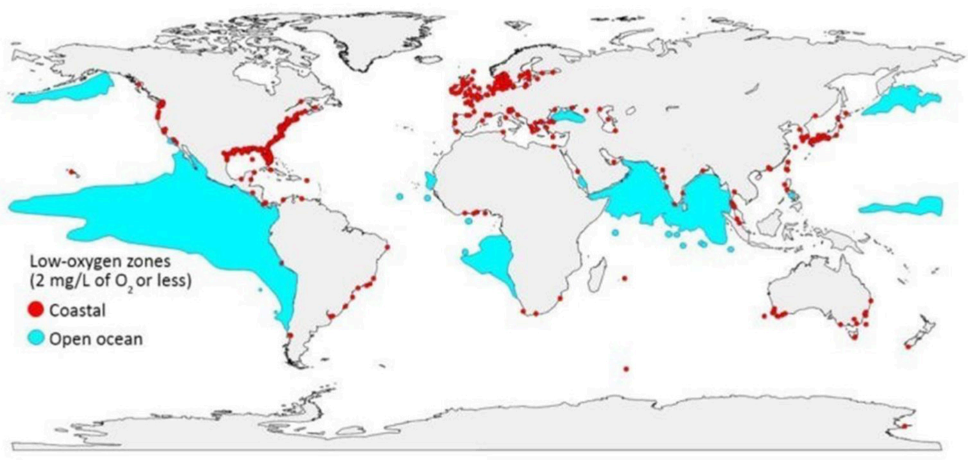


Figure 1

Figure 1

Wastewater pollution results in multiple environmental problems. For example, large regions of the world's oceans can become depleted of oxygen. These regions are called low-oxygen zones. The oxygen concentration of healthy water is 10 milligrams per liter (10 mg/L) and the map shows large areas of oceans, colored blue, and coastal areas near cities, colored red, where the oxygen concentration is much lower. Nutrients from wastewater and from agriculture are the primary cause of oxygen minimum zones. Oxygen measurements are not available for every location on the planet, but this map shows the scope of the problem [1].

BIODEGRADATION

Bacteria and microalgae can eat many pollutants in a process known as biodegradation.

is done using gravity—by letting the wastewater sit in large tanks so the particles can settle to the bottom. The wastewater is now ready for the next step of treatment, which normally uses bacteria to remove contaminants from wastewater. How is this possible? Well, the bacteria eat the pollutants and clean up the water. There are several technologies that use bacteria to treat wastewater, and one example is called the activated sludge system, which has been around for over a century. This system contains an aeration tank, where bacteria are supplied with oxygen so they can clean the wastewater in a process called **biodegradation**. Supplying oxygen to bacteria is expensive, and the bacteria still do not eat all the phosphorus and nitrogen. After treatment, the bacteria are separated from the treated water in a settling tank. The third step in wastewater treatment is to kill any remaining bacteria to produce treated wastewater that is released to the environment.

What about the stubborn pollutants that remain in the water? The water may need further treatments, including filtration, ultraviolet light, and a chemical called ozone, to sterilize it and remove the remaining pollutants—but even these treatments do not sufficiently remove all nutrients.

HOW CAN MICROALGAE IMPROVE WASTEWATER TREATMENT?

Scientists have shown that microalgae can be used to improve the efficiency of the wastewater treatment process. Along with breaking down contaminants, microalgae also produce oxygen, consume carbon dioxide, and remove nutrients like phosphorus and nitrogen from the wastewater more completely than traditional wastewater treatment does. And it is less expensive, too!

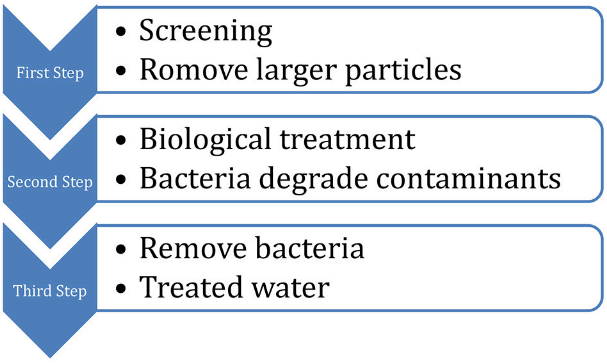


Figure 2

Figure 2

Current wastewater treatment processes. Bacteria are currently used in wastewater treatment, but more complete removal of nutrients could be achieved using microalgae in the second step of treatment. By using microalgae along with bacteria, the excess nutrients normally present in wastewater can be removed. The bacteria and microalgae produced during the treatment of wastewater contain nutrients removed from the wastewater, and can be recycled as fertilizer to help farmers.

Even better, the large amounts of algae, called algae **biomass**, grown at wastewater treatment plants could then be used to produce products including **biofuels** (replacements for fossil fuels like gas or oil) and **bioplastics** (replacements for traditional plastics) [2, 3]. The biomass that is leftover could be composted and converted into fertilizer to support farming. This technique basically allows the nutrients removed from wastewater to be recycled.

Production of biofuels from microalgae is usually expensive, with the cost and availability of chemical nutrients, especially phosphorus, being a key limitation [4]. The cost of producing biofuels can be decreased if wastewater is used as a source of nutrients for microalgae. Figure 1 shows that massive amounts of algae *can* grow using nutrients in wastewater [1]. So, instead of releasing nutrients from wastewater into to the environment and creating massive amounts of algae biomass in the oceans, this algae biomass could be created at future wastewater treatment plants that then recycle the nutrients. This technology has not yet been widely used [5], but scientists and engineers could make it happen, and future wastewater treatment plants could instead be called **resource recovery facilities**.

THE FUTURE OF WASTEWATER TREATMENT

To protect the planet, one of the 17 goals set out by the United Nations is to ensure safe water and safe wastewater disposal for all. Making valuable products while effectively treating wastewater is a good way forward! Wastewater treatment technologies of the future will not only produce clean water, but will also capture the precious nutrients, that were in poo, in the form of biomass. Captured biomass can then be used to produce biofuels, bioplastics, and fertilizers.

The conversion of wastewater treatment plants to resource-recovery facilities will be a major challenge requiring technological advances in many fields, including engineering, robotics, biology, chemistry, and public health. Wastewater treatment facilities at universities

BIOMASS

Biomass is renewable organic matter obtained from plants and animals. It holds the stored energy from the sun that plants capture through photosynthesis. Photosynthesis is the process by which plants use sunlight, water, and carbon dioxide to create oxygen and energy in the form of sugar.

BIOFUELS

Microalgae and bacteria can make chemicals that can be used as fuel, such as diesel, ethanol, and methane. Fuels made by microalgae and bacteria are called biofuels.

BIOPLASTICS

Some chemicals made by microalgae and bacteria can be used as substitutes for plastics made from petroleum. Bioplastics are plastic-like materials made by living things.

could provide ideal sites for developing the necessary technologies and could also provide educational and training opportunities. All developed areas on Earth need wastewater treatment. Might your future job be at a resource recovery facility?

RESOURCE RECOVERY FACILITY

An improved wastewater treatment plant that not only cleans wastewater, but also recovers and recycles nutrients is a resource recovery facility.

ACKNOWLEDGMENTS

The authors acknowledge the value of collaboration to understand and address environmental problems.

REFERENCES

1. Breitburg, D., Levin, L. A., Oschlies, A., Gregoire, M., Garcon, V., Gutierrez, D. et al. 2018. Declining oxygen in the global ocean and coastal waters. *Science* 359:eaam7240. doi: 10.1126/science.aam7240
2. De Mendonca, H. V., Otenio, M. H., Marchao, L.,Lomeu, A., de Souza, D. S., and Reis, A. 2022. Biofuel recovery from microalgae biomass grown in dairy wastewater treated with activated sludge: the next step in sustainable production. *Sci. Tot. Environ.* 824:153838. doi: 10.1016/j.scitotenv.2022.153838
3. Samadhiya, K., Sangtani, R., Nogueira, R., and Bala, K. 2022. Insightful advancement and opportunities for microbial bioplastic production. *Front. Microbiol.* 12:674864. doi: 10.3389/fmicb.2021.674864
4. Kilbane II, J. J. 2021. Shining a light on wastewater treatment with microalgae. *Arab. J. Sci. Eng.* 47:45–56. doi: 10.1007/s13369-021-06444-3
5. Valchev, V., and Ribarova, I. 2022. A review on the reliability and readiness level of microalgae based nutrient recovery technologies for secondary treated effluent in municipal wastewater treatment plants. *Processes* 10:399. doi: 10.3390/pr10020399

SUBMITTED: 17 July 2022; **ACCEPTED:** 10 August 2023;
PUBLISHED ONLINE: 29 August 2023.

EDITOR: Emily King, Xiamen University, China

SCIENCE MENTORS: Manuel Esperon-Rodriguez and Balaji Aglave

CITATION: Kilbane JJ II, Roubik H, Kovacs AJ, Keshinro T, Patel M and Feijter Jd (2023) Poo is Precious. Front. Young Minds 11:996462. doi: 10.3389/frym.2023.996462

CONFLICT OF INTEREST: Author AK was employed by the company KUKK K&F Ltd.

The remaining 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

JOSEPHINE, AGE: 12

My name is Josephine, I am 12 years old and I am in 6th grade. I live with my mom and dad, my four parakeets and a husky. My favorite color is neon-orange, I figure skate, swim, and play golf. I like to read and watch shows about animals, dragons, and mythology. I love animals, but I do not have a favorite since all have different skills and features. I enjoyed working on the article and I hope to do another one.

TANISHKA, AGE: 14

Possessing a strong affinity for science/health, Tanishka enjoys participating in numerous science competitions. She persistently receives 1st fair in STEM Fair and has gotten the Best of Fair award. She has also published two scientific articles in high-impact-factor journals. She is a part of numerous health-science-related clubs such as HOSA and has gotten 1st place at the international level in the HOSA international conference. Tanishka can be found playing her violin or reading whenever not studying or part-taking in competitions.

AUTHORS

JOHN J. KILBANE II

As an environmental microbiologist I have devoted my career to using biotechnology to address environmental issues such as cleaning contaminated soil and water, and the production of biofuels like biomethane, biodiesel, and ethanol. I am a retired Professor from the Illinois Institute of Technology and my current interests are motivating young scientists to improve wastewater treatment using microalgae to produce clean water, recycle nutrients needed by agriculture, and produce sustainable products like bioplastics and biofuels. *john_k61@yahoo.com

HYNEK ROUBIK

Associate Professor Dr. Hynek Roubik is a Group leader of Biogas Research Team (Czech University of Life Sciences Prague). He deals not only with aspects related to biogas, but also with waste management issues in general. He has participated in numerous research and development projects throughout the world as project leader or expert (i.e., Czechia, Vietnam, Cambodia, Ukraine, Uzbekistan, Georgia, Sri Lanka, Indonesia, and others). He does research especially in Waste Management, Environmental and Ecological Engineering, and is an editorial board member of several journals. He is the author of over 50 peer-reviewed (indexed) research papers. He was also appointed as one of the youngest associate professors in Czechia. In his free time, he likes to popularize science and play sports and work in the garden.

ANDRAS J. KOVACS
Emerging from petroleum refinery technology and petrochemisty R&D and teaching I have turned my focus to environmental technologies. I have believe that the best use of algae is their symbiosis with facultative microorganisms. I am confident that young minds will approach problems from multidisciplinary viewpoints on the ground of sound knowledge of mechanisms and connections of systems involved. I am looking forward to receive questions of clever young scientists.

TAOBAT KESHINRO
Taobat is a microbiologist and a lecturer at Lagos State University, Nigeria. She is an early career researcher interested in microbial interactions in natural environment. She is particularly interested in how mutualist relationship between microalgae and bacteria can solve global issues like sustainability, improved sanitation, as well as food and energy production. She is passionate about wastewater treatment, bioremediation, and algal biotechnology. *taobat.keshinro@lasu.edu.ng

MAULIK PATEL
Dr. Maulik Patel working as Post-Doc at USDA facility. He is working on antimicrobials other than antibiotics to mitigate microbial contamination to biorefineries. He has expertise in functional genomics and synthetic biology and agricultural waste liquefaction using enzymatic treatment. He has teaching experience to undergrads and master students at university level and trained many students for biotechnology skills. He also holds entrepreneur expertise in probiotics and developed various strains to be used as spore probiotics for feed animals and biofertilizer. He published various articles covering these topics. He enjoys reading and swimming in his free time, and has a passion for learning new things, application-based research.

JACOB DE FEIJTER
Jacob is a student at Te Wananga o Aotearoa in New Zealand. He is interested in environmental issues and spends his free time racing outrigger canoes and bicycling.

EARTH SCIENCES
Published: 01 August 2023
doi: 10.3389/frym.2023.998004

KELP IN A CHANGING ARCTIC OCEAN

Megan Shipton*[1,2*]*, Anaïs Lebrun*[2] *and Steeve Comeau*[2]

[1] *Université Côte d'Azur, Marres, France*

[2] *Sorbonne Université, CNRS, Laboratoire d'Océanographie de Villefranche, Villefranche-sur-mer, France*

YOUNG REVIEWERS:

ARIA
AGE: 10

LEAF
AGE: 9

In the northernmost part of our planet, in the icy cold coastal waters of the Arctic Ocean, you will find underwater forests filled with fish, crabs, and sea urchins. Unlike forests found on land, these underwater forests are made up of large brown marine algae called kelp. The various kelp species that make up the underwater forests are important in the Arctic Ocean. As temperatures continue to rise because of climate change, the future of Arctic kelp is unknown. In this article, we will discuss how changes in the Arctic climate, from melting ice to changes in ocean saltiness, may affect these underwater worlds.

UNDERWATER FORESTS

ECOSYSTEM

A set of organisms that interact with each other and with their environment.

Imagine walking through a forest full of trees, and seeing all the plants and animals that call the forest home. What you are imagining is an **ecosystem** created by the trees. Now, hold your breath and imagine a similar forest under the ocean. Not just any ocean—the icy-cold Arctic Ocean. You can stop imagining because these underwater forests exist. They are commonly found along the coasts of oceans all over the world, including the Arctic!

Underwater forests are similar to forests on land but, instead of trees, there are large, brown **marine algae** that can be several meters tall. They are called **kelp** (Figure 1). Like trees, kelp make their own food using sunlight, carbon dioxide, water, and nutrients found in the water. This is called photosynthesis.

Figure 1

Kelp create an environment like trees do on land: they generate shade and soften not the wind, but the waves. Kelp forests provide a safe, protected place for animals to hide and reproduce. These forests are a perfect home for fish, crabs, and sea urchins.

The same way you can find many kinds of trees in a forest, you can find many kinds of kelp in kelp forests. Lots of kelp species have been described in the Arctic Ocean. Understanding these species is important, because it tells scientists how healthy the forest ecosystem is [1].

A CHANGING ARCTIC OCEAN

Before we discuss the kelp that are found in the Arctic Ocean, it is important to understand the environment and conditions that they live in. Kelp forests have adapted to the temperatures and light found in the areas of the world where they live. In the Arctic Ocean, kelp forests have adapted to live in freezing temperatures and long periods of darkness in the winter. They can even grow underneath the sea ice! Today, all the northern conditions that Arctic kelp have adapted to are changing.

MARINE ALGAE

Plants that grow in saltwater environments like oceans, seas, and estuaries. The plants come in different shapes, sizes and colors.

KELP

A type of large seaweed that belongs to the brown **marine algae** family.

Figure 1

The Arctic kelp communities located in Kongsfjorden, an inlet on the west coast of Spitsbergen, which is an island that is part of the Svalbard archipelago in the Arctic Ocean. You can see the forest-like habitat created by several kelp species in this coastal region of the Arctic.

What is changing in the Arctic? As a result of climate change, temperatures are getting warmer. The air temperature in the Arctic rose by 3°C over the last 50 years. This is three times higher than the rise in temperatures seen in the rest of the world! Ocean temperatures have also risen. The sea-surface temperature of the Arctic Ocean has warmed twice as fast as the sea surfaces in the rest of the world [2]. This warming has a dramatic impact on the sea ice. In the summer, Arctic sea ice is melting more quickly than we have ever seen before. The ice is also freezing more slowly in the winter. Taken together, these changes mean that there is less sea ice in the Arctic than there used to be—up to 40% of the sea-ice cover has been lost. The **glaciers** and **permafrost** in the Arctic are melting, too. This makes the coastline more fragile.

GLACIER

A large mass of ice, snow, rock, sediment, and often liquid water that starts on land.

PERMAFROST

A thick layer of soil underneath the ground surface that remains frozen throughout the year in polar regions.

These changes in the Arctic kelp's environment affect how they grow and even whether they survive. The warmer temperatures cause other environmental factors to change too—which you will soon see, if you keep reading.

HOW CLIMATE CHANGE AFFECTS ARCTIC KELP SPECIES

So far, you know that underwater kelp forests are real and that they are important for Arctic life. You also know that climate change is changing the Arctic Ocean. Now we will tell you what we know about how kelp species are affected by the changes in the Arctic.

Let us start with temperature. Like temperatures on land, the ocean temperature is very important for underwater life. It also changes with seasons. In the winter, water temperatures in the Arctic Ocean average 0°C. In summer, water temperatures average 5°C, but can reach 10°C in the southern parts of the Arctic Ocean where it is warmer. Scientists that study Arctic kelp found that many species grow best between 10–15°C. So, the increasing temperatures in the Arctic Ocean are good for some kelp, helping them to grow well [3]. Other kelp species grow better in lower temperatures and might not survive as well as the waters warm. The kelp species that prefer colder temperatures and are only found in the southern region of the Arctic Ocean today may even start growing in the northern regions of the Arctic Ocean where the water temperature is slightly colder. Even kelp species that are usually found in the Atlantic Ocean are being found more frequently in the Arctic Ocean. This is because the Arctic waters are warming enough to be suitable for them, and this may result in a lot of changes to the kelp species found in the Arctic kelp forests. Warming waters might also change which animals live in in those forests.

SALINITY

A measure of how salty water is, so the amount of salt that is dissolved in water. The higher the salinity, the more salt there is in the water.

The amount of salt in seawater, called its **salinity**, is important as well. When ice melts on land, freshwater flows into the Arctic Ocean and dilutes the salt, therefore decreasing the salinity. The opposite happens when water freezes and salinity increases again. In the Arctic Ocean, salinity changes naturally due to the freezing and melting of ice with the seasons. But as more ice melts due to climate change, the salinity of the Arctic Ocean is decreasing. Just like with temperature, kelp species have ranges of salinity that are best for their growth. Studies have found that the growth of some kelp species can decrease if there is a strong decrease in salinity.

Use your imagination again: pretend that the sea ice is a lid that covers the water below. When there is less ice, or when the lid is no longer there, more light can reach into the water. Because kelp need light, a loss of sea ice could be good news for kelp forests. Scientists believe that the loss of ice in the Arctic will open up new areas for kelp to grow.

TURBIDITY

A measure of how murky water appears to be because of small particles that are suspended in the water. The higher the turbidity, the more particles there are in the water.

Turbidity is the last factor to consider. Turbidity describes the clarity of the water, or how see-through it is. The turbidity of water is determined by the number of particles present. The more particles, the higher the turbidity, and the more light is blocked from traveling through the water. This is not a good thing because, as you know, kelp need light to grow. The melting of glaciers and permafrost in the Arctic region is increasing the turbidity of the water in coastal regions, by bringing more soil particles, called sediment, into the ocean. Sediments block light from reaching kelp forests [4]. Therefore, as temperatures continue to increase and melting continues, increasing turbidity could make survival tough for Arctic kelp species.

KELP FORESTS OF THE FUTURE?

As you can see, when it comes to kelp forests, there are positive and negative outcomes of climate change in the Arctic Ocean. The impact that climate change will have also depends on the species, the specific region of the Artic, and the elements of the environment that are affected. Many ideas have been proposed to describe what the kelp forests of the Arctic might look like in the future. One idea is that kelp species that can handle the higher temperatures and lower salinities will dominate in the region, and the other kelp species will disappear from the forests. The animals that depend on the kelp species will likely follow the same trend (Figure 2).

CUMULATIVE EFFECT

Changes to the environment that are caused by more than one effect, like the effects of changes in temperature, salinity, and turbidity on the kelp forests.

It is important to understand that all the environmental elements are connected, so kelp may face many changes at the same time—like changes in temperature *and* salinity. We call this the **cumulative effect** of climate change, and it is difficult to predict. For example, scientists did an experiment on one kelp species that does not like high temperatures or low salinities, and when the two negative conditions were combined, the kelp grew even slower and struggled to photosynthesize [5]. Understanding the cumulative effect

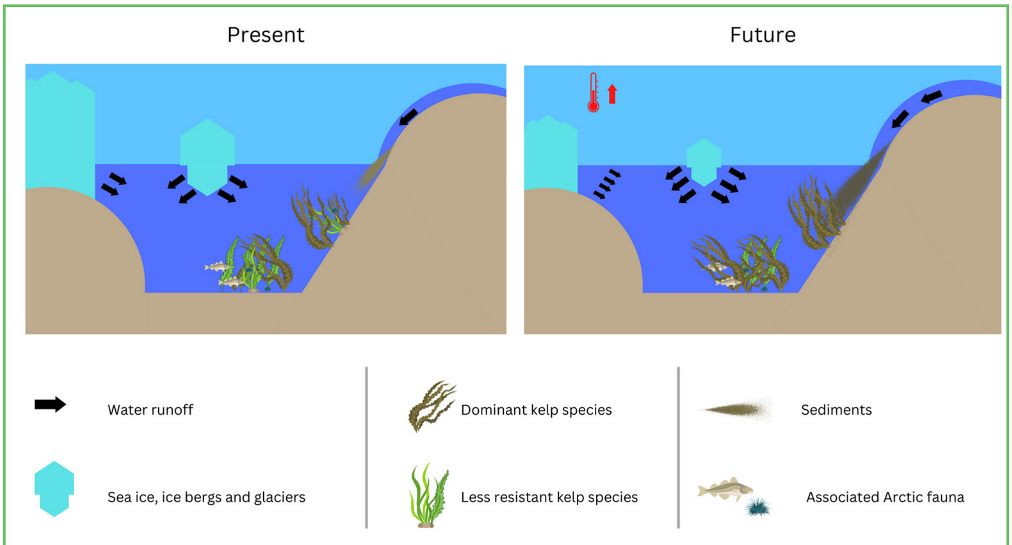


Figure 2

Figure 2

Present and predicted future conditions of coastal Arctic kelp communities. In the future, there will probably be increased water runoff from glaciers, icebergs, sea ice, and land resulting from increased temperatures in the Arctic. Waters are more turbid in the future, as more water runoff from land brings sediments into the water. The dominant kelp species will persist into the future, while the species that are less resistant to new conditions will probably disappear. The animals that live in Artic kelp forests, like sea urchins, may also change as conditions change in the future.

of climate change on kelp is a big challenge for scientists studying kelp today.

ACKNOWLEDGMENTS

This work is a contribution to the ORCA (Benthic organisms and communities in a changing Arctic) project (3051) funded by Foundation Prince Albert II de Monaco (www.fpa2.org).

REFERENCES

1. Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K., Pedersen, M. 2019. Arctic kelp forests: diversity, resilience and future. *Global Planet. Chang*. 172:1–14. doi: 10.1016/j.gloplacha.2018.09.005
2. IPCC. 2019. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate,* Pörtner, H. O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., et al. Cambridge; New York, NY: Cambridge University Press.
3. Krause-Jensen, D., Duarte, C. M. 2014. Expansion of vegetated coastal ecosystems in the future Arctic. *Front. Marine Sci*. 1:77. doi: 10.3389/fmars.2014.00077
4. Aumack, C., Dunton, K., Burd, A., Funk, D., and Maffione, R. 2007. Linking light attenuation and suspended sediment loading to benthic productivity within an Arctic kelp-bed community. *J. Phycol*. 43:853–863. doi: 10.1111/j.1529-8817.2007.00383.x
5. Diehl, N., Karsten, U., and Bischof, K. 2020. Impacts of combined temperature and salinity stress on the endemic Arctic brown seaweed Laminaria solidungula J. Agardh. *Polar Biol*. 43:647–656. doi: 10.1007/s00300-020-02668-5

SUBMITTED: 19 July 2022; **ACCEPTED:** 13 July 2023;
PUBLISHED ONLINE: 01 August 2023.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Xiaoming Wan and Yang Song

CITATION: Shipton M, Lebrun A and Comeau S (2023) Kelp in a Changing Arctic Ocean. Front. Young Minds 11:998004. doi: 10.3389/frym.2023.998004

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

ARIA, AGE: 10

Aria loves playing with her two guinea pigs and feeding birds and squirrels in her backyard. She gave each squirrel a unique name and lots of peanuts. Aria is always curious about science and she has a lot of questions about nature, animals, and the universe. She also likes singing and drawing in her spare time.

LEAF, AGE: 9

I am in third grade, and my favorite subject is Art and Science. I love observing changes in the world. I like to work as a Young Reviewer as I can observe many more changes using scientist's equipment. In my spare time, I like hiking, swimming, and riding bikes with my friends.

AUTHORS

MEGAN SHIPTON

Megan is an M.Sc. student studying science, innovation, and valorization of marine resources student at the Universite Cote d'Azur in France. For her internship, she was involved in the ORCA (Benthic Organisms and Communities in a Changing Arctic) project that studies the response of Arctic kelp to changes in light, temperature, and salinity. In her research career, she hopes to pursue her strong interest in kelp species. *megan.shipton@etu.univ-cotedazur.fr

ANAÏS LEBRUN

Anaïs is a Ph.D. student from Sorbonne University, working on how the arctic communities living on the seafloor—including kelp—are responding to global change. She is part of a project called "Horizon 2020 Future of Arctic Coastal Ecosystems—Identifying Transitions in Fjord Systems and Adjacent Coastal Areas",

which aims to help manage arctic fjord systems better, considering the quick changes happening in the ice-covered and biodiversity. Anais looks at how these changes are affecting the body functioning and its potential impacts on the entire community.

STEEVE COMEAU

Steeve is a research scientist from the Centre National de la Recherche Scientifique, working in the Laboratoire d'Océanographie de Villefranche. He studies the effects of global change on a large range of marine ecosystems, from tropical corals to Arctic kelp communities. He is the leader of the project "Benthic Organisms and Communities in a Changing Arctic" funded by the Fondation Prince Albert II de Monaco. This project aims to study the response of Arctic kelp to changes in light, temperature, and salinity.

EARTH SCIENCES
Published: 24 July 2023
doi: 10.3389/frym.2023.832555

NATURAL HAZARDS IN THE OCEAN

Jess I. T. Hillman [1*], ***Suzanne Bull*** [1] ***and Sally J. Watson*** [2,3]

[1] *Earth Structure and Processes, GNS Science, Lower Hutt, New Zealand*
[2] *Ocean Geology, National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand*
[3] *Institute of Marine Sciences, University of Auckland, Auckland, New Zealand*

YOUNG REVIEWERS:

LAUREL
AGE: 11

Over 70% of the Earth's surface is covered by the oceans. The seafloor beneath the oceans is a dynamic, active environment, and is where we find several important natural hazards, including underwater landslides, earthquakes, and tsunami. Some of the events that happen in the ocean can have a huge impact on land and are dangerous to people that live near coastlines. To understand how and why these natural hazards happen, we must know what is happening at the seafloor. Unfortunately, about 75% of the seafloor has still not been mapped. In this article, we will describe what causes these hazards and how we can find out more about them.

WHAT ARE NATURAL HAZARDS?

HAZARD

Anything that that can cause harm or damage to life or property.

A **hazard** is any natural event that can be dangerous to people or can damage buildings, roads, or properties. Examples include storms, floods, hurricanes, landslides, earthquakes, and tsunami waves. Sometimes, more than one natural hazard can happen at the same time. For example, a hurricane can cause flooding and heavy rainfall, which can then cause a landslide. Their effects on each other make natural hazards quite complicated, but this also means it is very important that we understand how and why natural hazards happen. This article looks at natural hazards that occur in the oceans.

The oceans cover over 70% of the Earth's surface, and over 40% of the world's population lives within 100 km of the coast (Figure 1). About 600 million people live in places that are <10 m above sea level. Because of this, things that happen in the oceans can have a big impact on people.

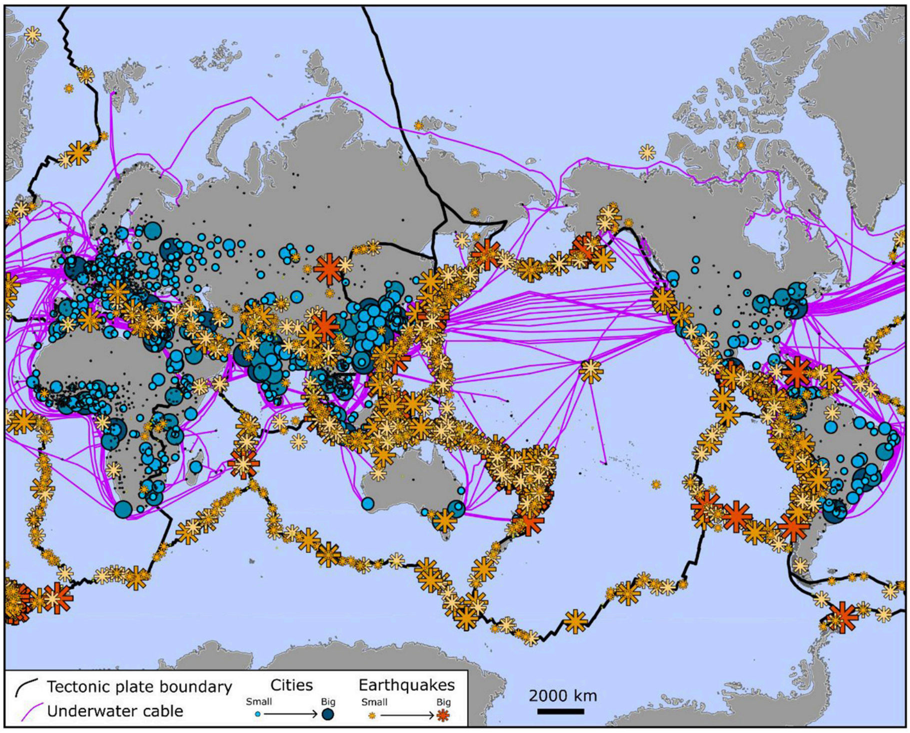


Figure 1

Figure 1

This map of the world shows underwater cables (purple lines) and tectonic plate boundaries (black lines). The blue circles show the locations of large cities. The orange stars show the locations of earthquakes from 2020 to 2021. As you can see, many people live in big cities in areas where large earthquakes happen, and many of them are near the oceans. This means that many people are at risk from the oceans' natural hazards.

TECTONIC PLATES

Tectonic plates are gigantic, irregularly shaped slabs of solid rock that make up the Earth's outermost layer, the crust.

PLATE BOUNDARY

The region where two or more tectonic plates meet. The plates can be moving toward each other, away from each other, or past each other.

EARTHQUAKE

An intense shaking of Earth's surface, caused by movements in Earth's outermost layer, the crust.

EARTHQUAKES

The Earth's crust (the outer, hard layer of Earth upon which we live) is made up of large, brittle **tectonic plates** that move and change over time. Where two plates meet, they form what is called a **plate boundary** (read more in *this Frontiers for Young Minds article*). Tectonic plates are continually moving, and at plate boundaries, they can get stuck due to friction. When the force along a plate boundary overcomes the friction, energy is released in waves that travel through the Earth and cause **earthquakes**. Earthquakes can happen on land and under the oceans, but mostly occur along plate boundaries, as you can see in Figure 1. Big earthquakes can cause a lot of damage and, in the oceans, they can also cause other hazards such as tsunamis and underwater landslides.

UNDERWATER LANDSLIDES

A **landslide** occurs when a large amount of **sediment** (mud, soil, and rocks) becomes unstable and falls down a hill or slope. On land, landslides are sometimes known as "slips" but they can also happen underwater.

LANDSLIDE

The movement of a large amount of rock, debris, or sediment down a slope.

SEDIMENT

Solid material made up of rocks, minerals, and the remains of plants and animals. It can be as small as a grain of sand or as large as a boulder.

We do not fully understand why underwater landslides happen. There are lots of things that can trigger a landslide in the oceans [1]. For example, a large volume of sediment might be quickly dumped onto the seafloor from rivers, due to a flood on land. This extra sediment can make the seafloor unstable, and a landslide might occur. You can think of this as a bit like building a sandcastle. If you add too much sand at the top, the sides will collapse because they cannot support the weight of all that sand.

Earthquakes are a common trigger for landslides. Imagine if you had a pile of sand in a bucket. If you shake the bucket, does the sand stay where it is or does some of it fall down the sides? In the same way, landslides can happen because the seafloor is shaking during an earthquake.

Underwater landslides can be all sorts of shapes and sizes. Some of them are very small and hardly noticeable in seafloor maps, about the size of a football pitch or just a bit bigger (100 m^2). Others can be really huge. The biggest underwater landslide that we know of happened off the coast of South Africa and is called the Agulhas Slide [2]. When this landslide happened, around 20,000 km^3 of sediment went cascading along the seafloor, traveling over 750 km. This is about the volume of 800 billion Olympic-sized swimming pools!

Sediment moving across the seafloor during an underwater landslide can damage the homes of living things as well as underwater cables and pipelines [1]. Did you know that over 99% of internet data is sent around the world through cables on the seafloor? These cables are very important for helping us communicate with people around the world, and they are difficult and expensive to repair.

Underwater landslides can also form tsunami waves, which are very dangerous for people living near the coast.

TSUNAMI WAVES

Tsunami is a Japanese word that means "harbor wave." Tsunami waves are unusually large waves that get bigger as they approach the shallower water of the coast, and they can cause a lot of damage. There have been several large tsunami waves recorded in the past 20 years. Tsunami waves that are large enough to cause damage or injury happen about twice a year. In the Indian Ocean on December 26, 2004,

TSUNAMI

A giant wave caused by movement of the seafloor.

waves as tall as buildings hit the coast of Indonesia, Sri Lanka, India, and Thailand, causing a huge amount of damage and resulting in the loss of 227,898 lives [3]. More recently, in 2011, a 40 m high wave damaged the coast of Japan, where more than 450,000 people lost their homes and 15,500 people were killed [4]. This tsunami wave also hit a nuclear power plant, damaging the emergency power generators and leading to a series of explosions and the release of radioactive material.

Both earthquakes and underwater landslides can create tsunami waves because they can move the seafloor, which displaces the water in the ocean above (Figure 2). Think about what happens when you throw a stone into a pond—the stone causes ripples that travel across the surface of the pond. Tsunami waves can travel long distances across oceans, sometimes traveling as fast as a jet plane! Unlike normal waves

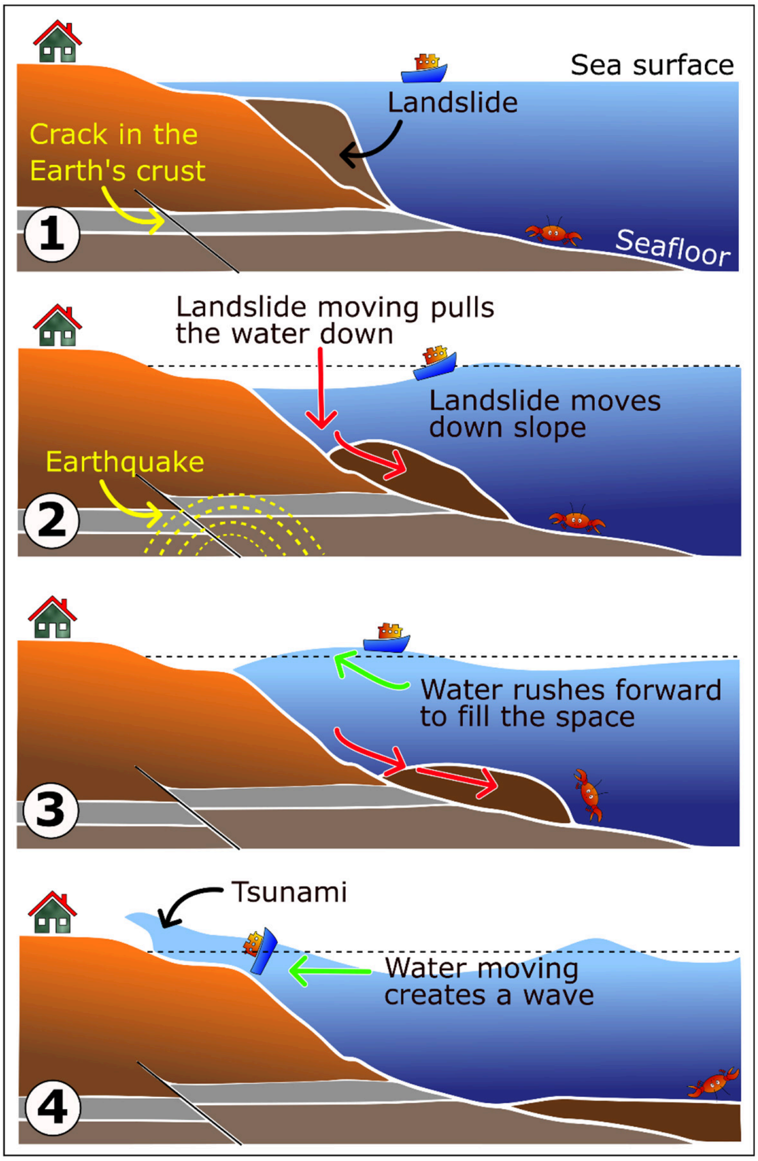


Figure 2

Figure 2

(1) Under the seafloor, there are layers of sediment. **(2)** A landslide is triggered, in this case by an earthquake. **(3)** Water fills the space where the landslide happened, creating a tsunami wave. **(4)** The tsunami wave gets bigger as it moves into shallow water near the coast.

you might see at the beach, which only affect the water close to the surface, tsunami waves occupy the entire water column, from the seafloor to the sea surface. Because of this, when these powerful waves reach the coast and move into shallower water, the waves' energy becomes more concentrated, increasing the wave height and allowing the waves to travel a long way onto the land.

HOW CAN WE STAY SAFE FROM FUTURE HAZARDS?

Large areas of the seafloor have still not been mapped in detail (see *this Frontiers for Young Minds article*). So, there are probably lots of underwater landslides that we have not found yet. Mapping more of the seafloor in detail will help us to better understand where landslides are and why they happen. Over the last 5 years, seafloor maps have improved a lot, and we now have detailed maps covering about a quarter of the seafloor worldwide. But we cannot stop here! If we have complete maps of the entire seafloor, we can be better prepared for all hazards in the oceans. Most seafloor mapping is done by people on ships, and it can take a long time and cost a lot of money. But new remote-controlled robots are now available that can help us map more of the seafloor, faster. This is especially important in places near plate boundaries or where hazards might impact people living near the coast. In many areas of the world, there are large projects investigating natural hazards underwater, including off the coasts of New Zealand, Japan, and the USA. Hazards in the oceans can impact many countries. For example, tsunami waves from the January 2022 volcanic eruption in Tonga traveled all the way across the Pacific Ocean to Peru. So, it is important for scientists from many countries work together to help keep us safe from ocean hazards.

WHAT SHOULD YOU DO IF YOU EXPERIENCE THESE HAZARDS?

It is not possible to predict exactly when or where these hazards will occur, but they are more likely to happen in certain places, such as along plate boundaries. It is always best to be prepared so that you know what to do in the event of a hazard.

Earthquake—If you feel the ground shaking or moving, drop to the ground, get under cover (under a desk or table is a good place to be), hold on to something to support yourself, and protect your head and neck (Figure 3). Just remember, drop, cover, and hold!

Tsunami—If you notice the water retreating unusually far back from the beach or coast, move immediately inland to high ground and stay there until you know the threat has passed. If you are near the coast and you experience a long or strong earthquake, in which the ground moves so much that it is difficult to stand or the shaking lasts for

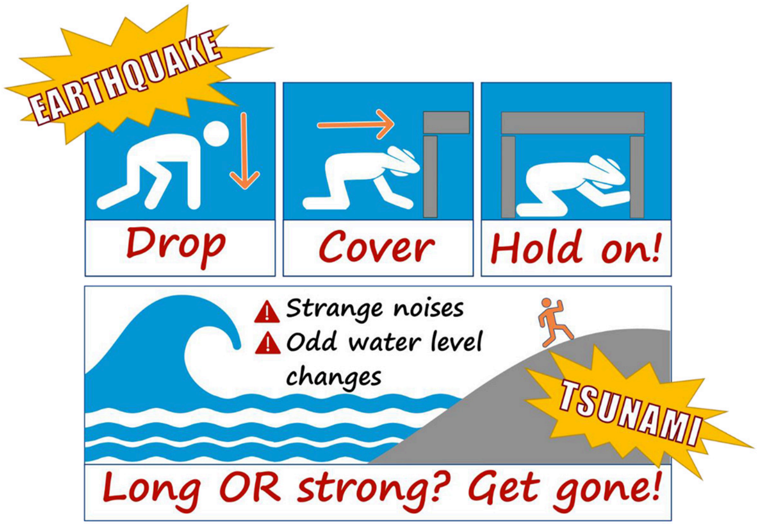


Figure 3

Figure 3

If you feel an earthquake, drop to the ground, get under cover, and hold on! If you are by the coast and you see the water level change suddenly, hear strange noises from the sea, or feel a long, strong earthquake—remember—get gone! Move to high ground as quickly as you can.

longer than a minute, you should again move to high ground as quickly as possible (Figure 3). This is because strong earthquakes can trigger tsunamis. So, remember, if it is long OR if it is strong, get gone!

Landslide—It is unlikely that you will experience an underwater landslide directly (unless you happen to be in a submarine), but you might experience a tsunami caused by an underwater landslide. Remember, if you are near the coast, follow the same guidelines as outlined for a tsunami wave. But do not forget that landslides are not always caused by earthquakes, they can occur without warning.

Natural hazards in the ocean, including earthquakes, landslides, and tsunami, affect large areas of the world, and can have devastating impacts on people that live close to the coast. Better understanding these hazards can help us to educate people on how to prepare for possible hazards, before they become disasters.

ACKNOWLEDGMENTS

This work was funded by the Ministry of Business, Innovation and Employment, New Zealand, under contract no. C05X2104 "Assessing silent tsunami risk in the Tasman Sea/Te Tai-o-Rēhua".

REFERENCES

1. Masson, D. G, Harbitz, C. B, Wynn, R. B, Pedersen, G., and Løvholt, F. 2006. Submarine landslides: processes, triggers and hazard prediction. *Philos. Trans. Royal Soc. A* 364:2009–39. doi: 10.1098/rsta.2006.1810

2. Dingle, R. V. 1977. The anatomy of a large submarine slump on a sheared continental margin (SE Africa). *J. Geol. Soc.* 134, 293–310. doi: 10.1144/gsjgs.134.3.0293
3. Lay, T., Kanamori, H., Ammon, C., Nettles, M., Ward, S., Aster, R., et al. 2005. The great Sumatra-Andaman earthquake of 26 December 2004. *Science* 308:1127–33. doi: 10.1126/science.1112250
4. Hayes, G. P., Myers, E. K., Dewey, J. W., Briggs, R. W., Earle, P. S., Benz, H. M., et al. 2017. *Tectonic Summaries of Magnitude 7 and Greater Earthquakes From 2000 to 2015: U.S. Geological Survey. Open-File Report 2016–1192*. Reston, VA: United States Geological Survey. p. 148. doi: 10.3133/ofr20161192

SUBMITTED: 10 December 2021; **ACCEPTED:** 23 June 2023;
PUBLISHED ONLINE: 24 July 2023.

EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Lynette Cheah

CITATION: Hillman JIT, Bull S and Watson SJ (2023) Natural Hazards in the Ocean. Front. Young Minds 11:832555. doi: 10.3389/frym.2023.832555

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

LAUREL, AGE: 11

Hello, I like mechanical engineering and Lego. I like to making things and tinkering. I like learning science.

AUTHORS

JESS I. T. HILLMAN

Jess (she/her) is a marine geologist and geophysicist. Her work is focused on investigating the geology (rocks) beneath the seafloor around Aotearoa New Zealand. *j.hillman@gns.cri.nz

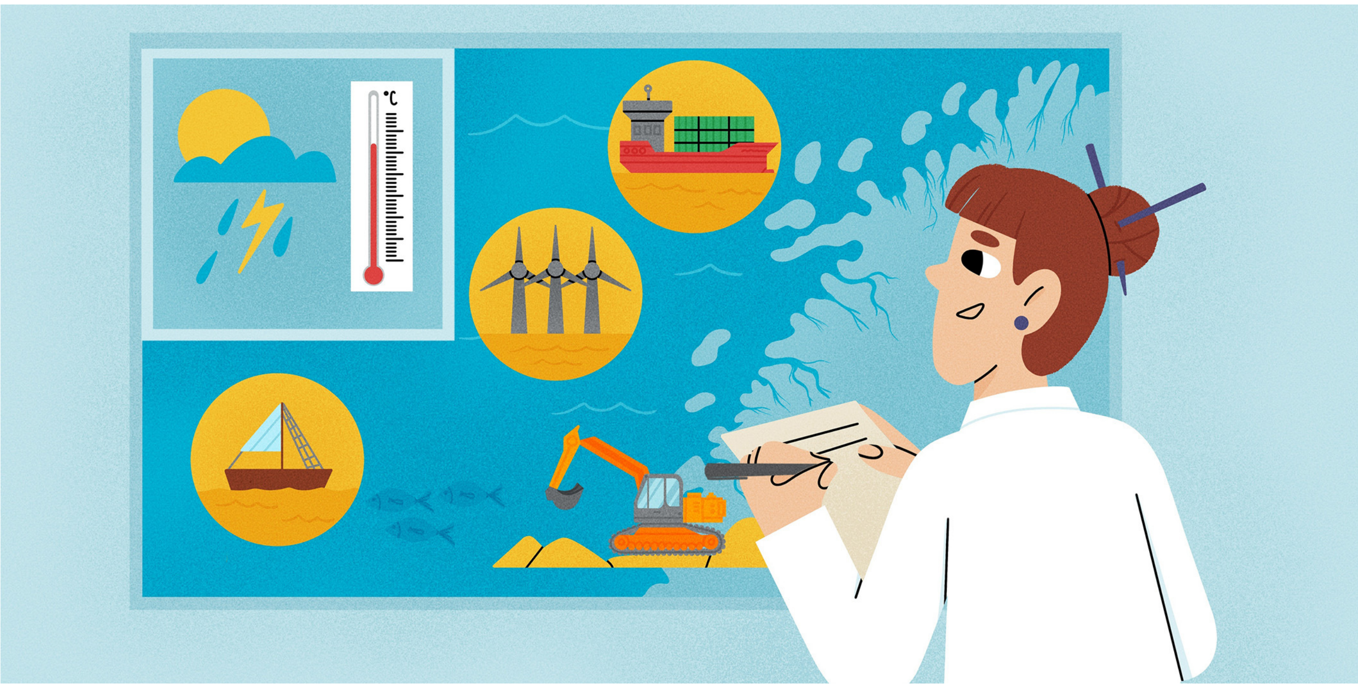
SUZANNE BULL

Suzanne (she/her) is a geophysicist. She uses sound waves to find out what is happening under the seafloor around Aotearoa New Zealand.

SALLY J. WATSON

Sally (she/her) is a marine geologist and geophysicist. Sally's research looks at how and why the seafloor changes over time.

EARTH SCIENCES
Published: 24 July 2023
doi: 10.3389/frym.2023.1029011



WHY WE MUST THINK ABOUT CLIMATE CHANGE WHEN PLANNING HOW TO USE OUR SEAS

Emilie Bréviére[1*], *Linus Hammar*[2], *Iréne Wåhlström*[1], *Jonas Pålsson*[3], *Lars Arneborg*[1], *Elin Almroth-Rosell*[1] *and Per Jonsson*[4]

[1] *Department of Research and Development in Oceanography, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*

[2] *Octopus Ink Research and Analysis, Gothenburg, Sweden*

[3] *Kelonia AB, Billdal, Sweden*

[4] *Department of Marine Sciences, Tjärnö Marine Laboratory, University of Gothenburg, Gothenburg, Sweden*

YOUNG REVIEWERS:


ALISSAR
AGE: 14


HADIL
AGE: 12


IMAN F
AGE: 15


MOHAMED AMINE
AGE: 12


NAKAE T
AGE: 14

Many activities take place at sea. For example, goods are transported by ships, people enjoy time by the beach, piers and buildings are constructed on the coastline, and fishermen fish. Human activities change the sea's environment and can harm ocean animals and plants. To find a good balance between using and protecting the sea, many countries have begun planning their ocean space—a process called marine spatial planning. Planners use tools developed by researchers to understand how various human activities will affect the sea in the future. When we added climate change into a software tool for marine spatial planning in Sweden, we found that climate change alone might be as harmful to the sea as all other human activities taken together! Climate change is strongly affecting the sea and should, therefore, be included in marine spatial planning.

YAHYA

AGE: 12

YOUSSEF

AGE: 12

MARINE PRESSURES

A lot of activities take place by the sea and at the beach. For instance, families enjoy a day out at the beach collecting shells, swimming, and having ice cream. Fishermen trawl the ocean with their nets to catch the fish we eat. Offshore windmills produce energy, and container ships transport goods from one place to another. All these activities affect the sea's environment, which means they impact marine animals and plants. There are other pressures on sea organisms that are not visible to our eyes. For example, chemicals, like the fertilizers and pesticides used in agriculture, are carried by rivers and released into the sea, causing pollution. Sometimes toxic products like oil or old ammunition are dumped into the sea, accidentally or intentionally. All these pressures threaten marine animals and plants. The sum of all these effects is called the **cumulative impact**.

CUMULATIVE IMPACT

Sum of the effect of all pressures from human activities on marine animals and plants.

MARINE SPATIAL PLANNING

People want to continue to experience the benefits of the ocean, and the number of things people want to use the ocean for is increasing. This makes the sea more and more crowded. Therefore, to prevent the sea from being damaged or destroyed, we must be cautious—we must find the appropriate balance between *using* and *protecting* a given sea area. To achieve this, in recent years many governments have begun using a process called **marine spatial planning** (MSP). MSP is a relatively new way of managing human marine activities. It is a long-term planning process that guides where, when, and how humans can use the ocean. MSP can help countries balance all the activities that happen in the sea and make sure that everyone benefits, while also protecting the marine environment.

MARINE SPATIAL PLANNING

A long-term planning process that guides where, when, and how humans can use the ocean.

MSP is based on communicating with marine users (such as fishermen, investors, and shipping companies), and it begins with an analysis of the current situation. Responsible planners gather as much information as they can on everything that is taking place in the sea, from protected nature areas to places where underwater mining is occurring. Then the planners can map these activities to see where they overlap, so that they can understand some of the key issues that the plan must address. For example, planners may notice that a military training area must be extended, or that a shipping route should be moved a bit to allow the construction of a windfarm. Proper planning must take cumulative impacts into account.

Sweden is located in Northern Europe, and its long coastline (3,200 km) has many islands and archipelagos. The sea is deeply rooted in Swedish culture—including sailing, fishing, sea kayaking, floating saunas, postcard-pretty red fishing sheds, and wild nature. At the same time, shipping is increasing in the sea around Sweden, as is the demand for renewable wind energy. Sweden does not produce oil or gas, but sand must be mined from the ocean to make concrete. In addition, naval defense is increasingly important, coastal tourism is growing, and the country's cultural heritage must be respected. MSP is necessary in Sweden, so that all these human activities can have space without interfering with each other and without causing excessive damage to the environment.

SYMPHONY: A TOOL FOR MSP

For MSP in Sweden, experts developed and used a tool called Symphony, which is a computer software representation of the marine environment [1]. Symphony compiles information from 32 maps representing various ocean ecosystems (for example, where cod and reefs of mussels are living) and 41 maps showing pressures from human activities (such as shipping and trawl fishing)—all from the sea around Sweden [2]. Symphony uses **sensitivity scores**, which indicate how much each ecosystem component is affected by each human pressure. For instance, cod might not care much if tourists fish or if windfarms are constructed, but they might be sensitive to pollution or industrial fishing.

SENSITIVE SCORE

Number indicating how much an ecosystem component is affected by a human pressure.

With all this information, Symphony calculates the cumulative impact for each pixel (small area) like this: it multiplies the occurrence of one ecosystem component in a pixel (for example, how much mussels are present in that area) by the importance of one pressure in the same pixel (for example, how much trawling is taking place in that area) and the corresponding sensitivity score (how sensitive mussels are to trawling). Symphony does this multiplication for all possible combinations of ecosystem components (32) and pressures (42) for that pixel and, finally, sums all the multiplications to obtain the cumulative impact in that pixel. By doing this for each pixel of the sea, Symphony creates a map of the cumulative impact [2]. This is a lot of math!

In Figure 1, you can see how much human activities are impacting the ecosystems along the coast of Sweden. Symphony also provides detailed results for a chosen location, for example it can show which pressure is having the largest effect on the marine ecosystem. In Swedish waters, the cumulative impact is high. Pressures like industrial fisheries, pollution, and high amounts of fertilizers dominate. Knowing where the environmental impact is high or low is crucial for MSP. With this knowledge, marine plans can be optimized to protect the ocean environment. For example, the most damaging activity in an area can be reduced or moved elsewhere, and activities that are not harmful for the local ecosystem can be prioritized.

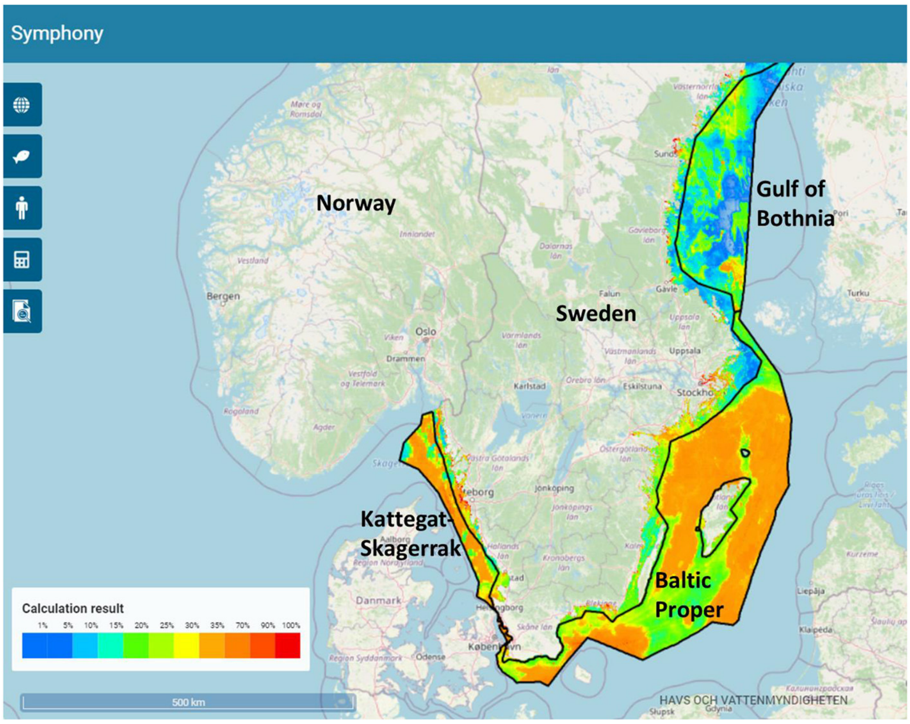


Figure 1

Figure 1

Symphony software generates a map showing the environmental impact of human activities on the sea along the coast of Sweden. Blues represent lower impacts and reds represent higher impacts. You can see that western and eastern Sweden are more impacted by human activities (orange-green), than northern Sweden (green-blue).

INCLUDING CLIMATE CHANGE IN SYMPHONY

As described above, marine planners use Symphony to get an idea of how their plans will affect the environment in the future. It is also important for planners to consider the future climate, which is likely to raise the cumulative impact even more. **Climate change** describes a change in the average weather conditions, such as temperature and amount of rain, in a region over a long period of time—at least 30 years. The changes are due to human activities that release **greenhouse gases**, which trap the sun's heat near Earth, warming the atmosphere and the ocean. Climate change modifies the ocean **salinity** (salt content), ocean currents, ice cover, and sea level. Possible future changes have been calculated for various amounts of greenhouse gas release, using computer-based climate models and oceanographic models for the sea surrounding Sweden [3].

This way, along with the 41 pressures from human activities, we added climate change into Symphony to assess how much stress it will cause on the marine ecosystems of the Swedish seas. Not all effects of climate change are included—only changes in temperature, salinity, and ice cover. All changes were modeled for the end of this century, meaning approximately the year 2100 [4].

The results from Symphony tell us that, in the future (when your grandkids are the age you are now!), the impact of climate change on the marine environment will be huge. It will be approximately as impactful as all the other 41 pressures from human activities put

CLIMATE CHANGE

A change in the average weather conditions, such as temperature or amount of rain, in a region over a period of time of at least 30 years.

GREENHOUSE GASES

Gases which have the capacity to trap the sun's heat in the atmosphere at the surface of the Earth and as a consequence warm it up.

SALINITY

Amount of salt dissolved in water.

together [4]. Far up north in the Gulf of Bothnia, climate change may even become a threat several times bigger than all the human activities of today combined (Figure 2).

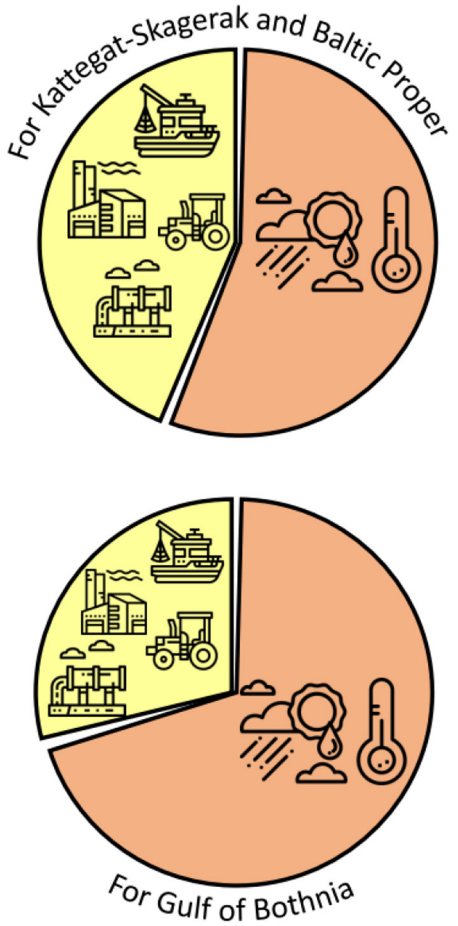


Figure 2

Figure 2

It is important for planners to consider the effects of climate change as one of the pressures on marine ecosystems. Results from Symphony indicate that this impact will be very large and will vary depending on location. For three marine regions around Sweden, you can see that Symphony forecasts climate change pressure (orange pie portion) to exceed all 41 other human-generated pressures combined (yellow pie portion; Figure credit: icons made by smalllikeart from www.flaticon.com).

CLIMATE CHANGE IN MSP IN SWEDEN

The researchers who developed Symphony have recommended that Swedish marine planners consider how climate change will affect separate areas of the sea in unique ways (Figure 3). Planners have been advised to plan marine activities in a flexible way that takes local conditions into account. This is called **adaptive management**, and it means that human activities such as fishing, shipping, and mining should sometimes be avoided in areas that are likely to remain healthy in the face of climate change. This will help these areas to stay strong and act as safe harbors for animals and plants as climate change progresses—such areas are called **climate refugia**.

Adaptive management might also mean that planners propose new sea-based activities when climate change is projected to modify the ecosystem of an area [4]. For example, if it is likely that an area will turn

ADAPTIVE MANAGEMENT

A form of environmental management in which actions are regularly updated based on new information and new knowledge.

CLIMATE REFUGIA

Areas that are less affected by climate change over time, and which may continue to be good places for threatened plants and animals to live.

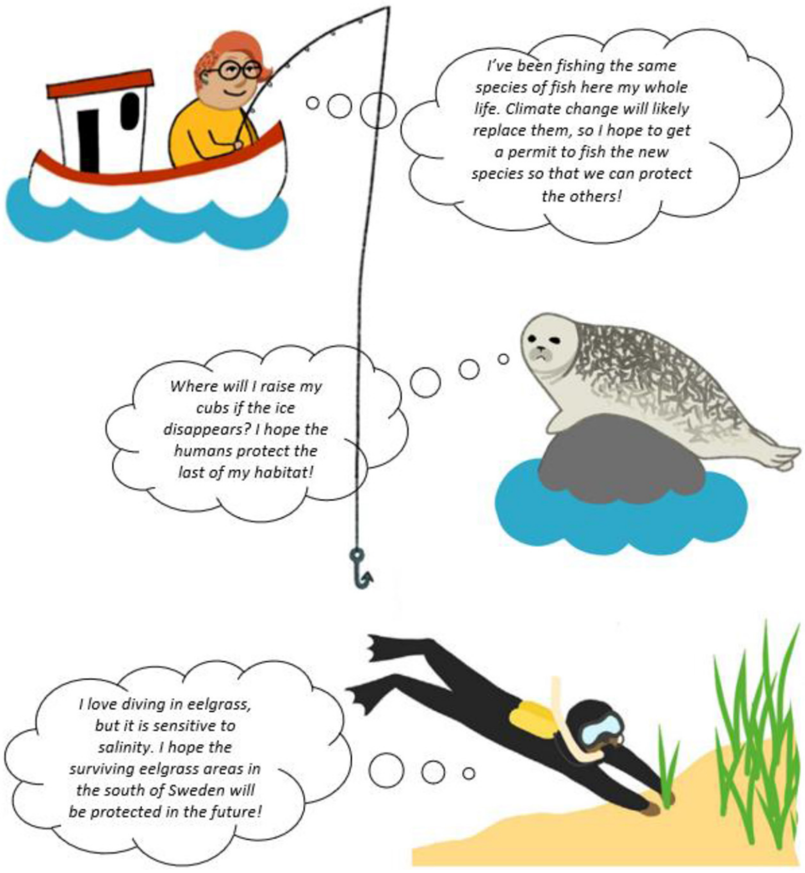


Figure 3

Figure 3

Examples of the challenges faced by marine spatial planning in a changing climate (figure credit: Malva Crona, CC-BY 4.0, International Public License).

into freshwater, planners can suggest preparatory measures that will strengthen freshwater ecosystems over time, as well as activities that involve the careful use of freshwater organisms.

Most importantly, marine planners must monitor the progress of climate change in the sea. Research is constantly improving, so management decisions must continuously adapt to new information. There are still many things we do not know about the effects of on-going climate change, but it will clearly have an enormous impact on the marine environment. The extent of this impact is a direct consequence of our decisions today and in the next decades. If we decrease our production of greenhouse gases and plan properly for future use of the sea, we may be able to conserve valuable ecosystems and continue to experience the benefits of the ocean.

ACKNOWLEDGMENTS

This work was financed by the ClimeMarine project, funded by the Swedish Research Council for Sustainable Development (Formas) within the framework of the National Research Programme for Climate (grant no. 2017-01949).

ORIGINAL SOURCE ARTICLE

Wåhlström, I., Hammar, L., Hume, D., Pålsson, J., Almroth-Rosell, E., Dieterich, C., et al. 2022. Projected climate change impact on a coastal sea—as significant as all current pressures combined. *Glob. Change Biol.* 28:5310–9. doi: 10.1111/gcb.16312

REFERENCES

1. Halpern, B. S., Walbridge, S., K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. 2008. A global map of human impact on marine ecosystems. *Science* 319:948–52. doi: 10.1126/science.1149345
2. Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., et al. 2020. Cumulative impact assessment for ecosystem -based marine spatial planning. *Sci. Total Environ.* 734:139024. doi: 10.1016/j.scitotenv.2020.139024
3. IPCC. 2021. "Climate change 2021: the physical science basis," in *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge; New York, NY: Cambridge University Press). p. 2391. doi: 10.1017/9781009157896
4. Wåhlström, I., Hammar, L., Hume, D., Pålsson, J., Almroth-Rosell, E., Dieterich, C., et al. 2022. Projected climate change impact on a coastal sea—as significant as all current pressures combined. *Glob. Change Biol.* 28:5310–9. doi: 10.1111/gcb.16312

SUBMITTED: 26 August 2022; **ACCEPTED:** 23 June 2023;
PUBLISHED ONLINE: 24 July 2023.

EDITOR: Sanae Chiba, North Pacific Marine Science Organization, Canada

SCIENCE MENTORS: Loai Aljerf and Nordin Ben Seddik

CITATION: Brévière E, Hammar L, Wåhlström I, Pålsson J, Arneborg L, Almroth-Rosell E and Jonsson P (2023) Why We Must Think About Climate Change When Planning How to Use Our Seas. Front. Young Minds 11:1029011. doi: 10.3389/frym.2023.1029011

CONFLICT OF INTEREST: JP was employed by Kelonia AB.
The remaining 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

ALISSAR, AGE: 14

I spend summer times swimming, riding around town, and playing in the park. My childhood was idyllic and I have many fond memories of those carefree days. I was involved in a lot of extracurricular activities, including the school band and the drama club. I am a member of some green sorority and involved in a lot of campus activities. I hope to land some small roles in independent films and commercials and do also some modeling work and being appeared in some TV shows and movies.

HADIL, AGE: 12

Hi, I am Hadil. I like sport and music but also science and physics. Sometimes I can be funny but I am also serious.

IMAN F, AGE: 15

My name is Iman, I am 15 years old, and my academic level is the third preparatory. My favorite subjects are physics and mathematics. My hobbies are reading, research and drawing. I have participated in school festivals. I speak French and I love English. My dream is to become an engineer.

MOHAMED AMINE, AGE: 12

Hello, my name is Mohamed Amine, I am a young reviewer. Technically, I am good in English. I like playing football with my friends and playing video games too. My favorite food is pizza. In the future, I want to be a doctor. So thank you for reading my biography.

NAKAE T, AGE: 14

My name is Nakae T, I am 14 years old. My school level is the third preparatory. My favorite subjects are: Art education and mathematics. My hobbies are: drawing and scientific research. Pizza is my favorite food. I have participated in the reading challenge contest. I speak French and English, my dream is to become a surgeon.

YAHYA, AGE: 12

Hello dear reader, I am Yahya, I am a young reviewer. Since I was 8 years old I liked everything about sciences and mathematics, my dream is to visit all the countries in the world, and thank you for reading my biography. Enjoy!

YOUSSEF, AGE: 12

Hello, I am Youssef. A young reviewer, I am good in English technically, so if you need anything that includes English you can ask me and I will try my best to help you. Thank you for reading my biography.

AUTHORS

EMILIE BRÉVIÈRE

Dr. Emilie Brévière is a marine biogeochemist with expertise in science management and coordination, in particular at the international level. Her interests are very broad as she is very curious—from global marine citizen science to a training programme on climate change in West Africa *via* understanding the carbon cycle in European seas, to monitoring of nutrients amounts in the Baltic Sea. *emilie.breviere@smhi.se

LINUS HAMMAR

Dr. Linus Hammar is a marine biologist with expertise in assessing environmental impact in the sea, which means how various human activities affect marine animals and plants. He has worked with renewable energy from the sea and his main job deals with skills development, together with partners in East Africa. Linus is also an author of children's books.

IRÉNE WÅHLSTRÖM

Dr. Iréne Wåhlström holds a Ph.D. in marine chemistry, and she specialized in the marine carbon system. She works at the Swedish Meteorological and Hydrological Institute in Sweden, on the biogeochemistry within the Baltic Sea and the Arctic Ocean. Her main interest is to understand how climate change will affect the marine environment in the future.

JONAS PÅLSSON

Dr. Jonas Pålsson is an expert on environmental impacts of human activities, especially shipping, oil spills, and marine spatial planning (MSP). He currently works on the marine environmental impact of human activities and cumulative environmental impact assessment using the Symphony tool, in Sweden and in the Western Indian Ocean.

LARS ARNEBORG

Dr. Lars Arneborg is a physical oceanographer with expertise on the physical ocean environment, for example how salinities, temperatures, and currents change when the weather or river runoff change—on short and long-time scales, such as climate change. His main focus is on coastal seas such as those surrounding Sweden.

ELIN ALMROTH-ROSELL

Dr. Elin Almroth-Rosell is a marine chemist with expertise in biogeochemical modeling, studying the marine environment and the effects of human pressures such as climate change. She is working in the oceanographic unit at the Swedish Meteorological and Hydrological Institute.

PER JONSSON
Professor Per Jonsson is a marine ecologist with expertise in how current global changes affect the ecology and evolution of marine organisms, and how to improve strategies for management and protection of the sea.

frontiers | Frontiers for Young Minds

BIODIVERSITY
Published: 22 June 2023
doi: 10.3389/frym.2023.812844

WHALE DETECTIVES USE CHEMISTRY CLUES TO UNCOVER THE SECRET LIVES OF BEAKED WHALES

Kerri J. Smith[1,2*], *Tarla Rai Peterson*[3] *and Markus J. Peterson*[4]

[1] *Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, United States*
[2] *Department of Vertebrate Zoology, National Museum of Natural History, Washington, DC, United States*
[3] *Department of Communication, University of Utah, Salt Lake City, UT, United States*
[4] *Department of Rangeland, Wildlife, and Fisheries Management, Texas A&M University, College Station, TX, United States*

YOUNG REVIEWERS:

UMBERTO
AGE: 12

Have you ever heard of a beaked whale? These fascinating but mysterious whales live far away from shore and stay under water for a long time, so it is challenging for scientists to learn about them. Some species of beaked whales are so mysterious that scientists have never even seen them alive! To help learn about beaked whales, scientists can study special chemicals, called stable isotopes, in the tissues of these whales to learn where they have been living. These whale detectives work with museums and coastal communities to get tiny pieces of whale skin, muscle, and bone, which the detectives then examine for stable isotopes. Using these chemistry clues, the whale detectives discovered that some beaked whales live in one area their entire lives. The whale detectives can use this information to find and study beaked whales in the wild and answer more questions about their lives.

BEAKED WHALES LIVE MYSTERIOUS LIVES

Take a moment and imagine a whale—maybe you picture a humpback whale, or a killer whale, or maybe even a bottlenose dolphin. These **cetaceans** (the group of animals that includes whales, dolphins, and porpoises) come to mind easily because we see and hear about them in books, movies, and the news. But have you ever heard of a beaked whale (Figure 1)? Most people have not heard about beaked whales because they live mysterious lives and scientists do not know very much about them [1].

CETACEAN

The scientific name for the group of animals that contains all whales, dolphins, and porpoises.

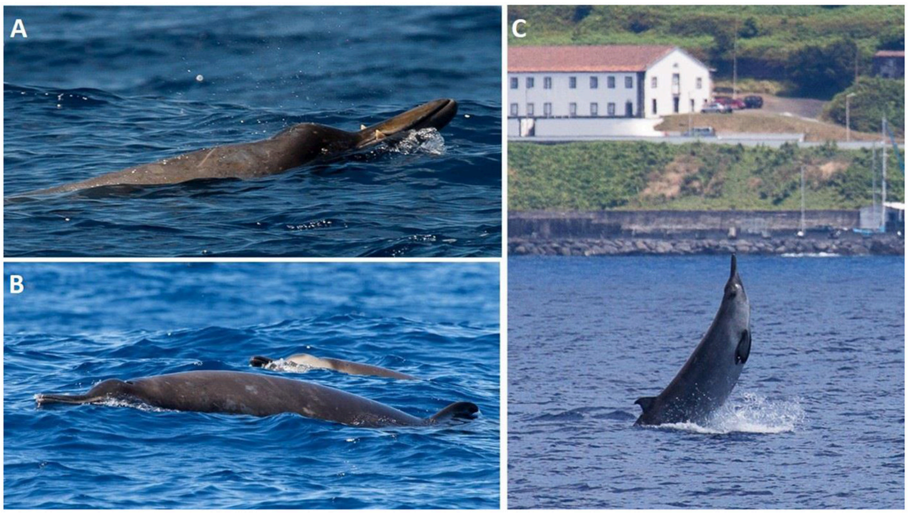


Figure 1

Figure 1

Photos of Sowerby's beaked whales in the wild. **(A)** A male with prominent teeth. **(B)** A female and calf. **(C)** A whale leaping from the water (Photo credits: Lisa Steiner at Whale Watch Azores).

What makes beaked whales so mysterious? Most cetaceans are a little mysterious because they live in oceans, and oceans are huge environments that are challenging for people to explore. Even the biggest whales are difficult to find and study. Cetaceans that are familiar to us tend to live in habitats close to shore, where they are easier to find and study, but beaked whales live in very deep water far from shore. Scientists may spend months on a boat looking for beaked whales and never find them. If scientists *do* find beaked whales, the whales can dive deep under water for 30 min or more, and the scientists may not be able to find them again when the whales finally come back to the surface. This secretive behavior makes it almost impossible for scientists to learn about beaked whales in the wild [2].

For hundreds of years, scientists have known that beaked whales exist—yet we know almost nothing about them because of their mysterious lifestyles. Most of what scientists do know about beaked whales comes from stranded whales. A **stranding** is when a whale is sick or dead and washes onto shore. We can look at the stranded whale's body to learn about what **species** (type) it is, and sometimes we can also learn what it was eating and how old it is. Using information from these strandings, scientists have discovered 24

STRANDING

When a whale, dolphin, or porpoise becomes stuck in on land; this can happen when an animal is sick or becomes lost and confused.

SPECIES

A group of the same type of organisms that look similar and can reproduce with each other.

different species of beaked whales, and we think there might be even more species! But we wanted to learn even more from stranded beaked whales—where they live, where their food comes from, and how much they move around.

STABLE ISOTOPES ARE NATURE'S CHEMISTRY CLUES

Have you ever heard someone say, "you are what you eat"? Well, when it comes to chemistry, this is true! When you eat a carrot, for example, you receive all the chemical elements inside that carrot, and the carrot received those elements from the soil, water, and fertilizer available while it grew. Over time, special versions of elements, called **stable isotopes**, build up in our tissues from the foods we eat and the water we drink (Figure 2) [3].

Figure 2

Isotopes are forms of the same element that differ in the number of **neutrons** in the **nucleus**. When comparing two forms of the same element, forms with more neutrons are called heavy isotopes and forms with fewer neutrons are called light isotopes. There are also **protons** inside the nucleus, and the number of protons does not change between isotopes of the same element. An isotope of an element that has the same number of protons as neutrons is considered the "regular" form of the element. Some isotopes are radioactive, meaning they decay or break down over time, but stable isotopes do not decay. We can use the element carbon as an example. Carbon has 15 isotope forms, but the most common are ^{12}C, ^{13}C, and ^{14}C. The "C" stands for carbon, and the small number before the C tells us the number of neutrons and protons (added together) that the carbon isotope has in its nucleus. All carbon atoms have six protons, so any difference in the isotope number is due to differences in the number of neutrons. ^{12}C is the regular form of carbon, with six protons

STABLE ISOTOPES

Isotopes are forms of a chemical element with different numbers of neutrons in the nucleus; stable isotopes do not break down over time.

Figure 2

The stable isotopes in our bodies come from the environment, through the foods we eat and the water we drink. Plants gain stable isotopes from the soil, water, and fertilizer where they are grown, and then those stable isotopes are passed on to us when we eat the plants. The ratio of heavy to light stable isotopes is unique in various regions of the world, so scientists can look at these ratios in the tissues of animals and people to see where they have been living and what they have been eating (Image credit: Aaron W. Kirkpatrick).

NEUTRON

A tiny, uncharged particle found inside the nucleus of an atom; the number of neutrons in the nucleus can change.

NUCLEUS

The center of an atom that contains neutrons and protons; the nucleus is positively charged from the protons.

PROTON

A tiny, positively charged particle found inside the nucleus of an atom; the number of protons in a nucleus is specific to each chemical element type.

and six neutrons, while ^{13}C has six protons and seven neutrons, and ^{14}C has six protons and eight neutrons. Of these three carbon isotopes, ^{12}C and ^{13}C are stable, and ^{14}C is radioactive.

Heavy stable isotopes are rarer than light stable isotopes, but they stay in our bodies longer than lighter isotopes do. When our bodies make more tissues, like skin or muscle, both heavy and light isotopes are used to make those tissues. Some of our tissues, like skin, grow rapidly and are replaced every few months, while other tissues, like bone, grow slowly and may take years to be replaced. Scientists can compare the ratio of heavy to light isotopes in tissues to determine where an animal has been living or where its food and water came from. If scientists have multiple tissues from the same animal, such as samples of skin and bone, we can even compare changes over the animal's life due to the differences in replacement times for the tissues!

STABLE ISOTOPES REVEAL BEAKED WHALE SECRETS

We focused our study on one species of beaked whale, Sowerby's beaked whale. This species was discovered in 1804 by James Sowerby and it lives in the North Atlantic Ocean, but almost nothing else is known about it. We reached out to museums across North America and Europe, asking to take samples from Sowerby's beaked whale skeletons in their collections. Many museums work with community-based whale-stranding response programs (to get skeletons from stranded whales) and stranding programs sometimes keep pieces of other tissue types, like skin and muscle. We worked with 25 museums to obtain samples from 102 Sowerby's beaked whales from the east and West Atlantic Ocean (Figure 3A). Most of these samples were bone, but we got muscle and skin samples from 46 whales. Since bone, muscle, and skin tissues grow at different rates, we could compare isotope values across the whales' lives, from more than 15 years ago (bone tissue), a year ago (muscle tissue), and a few months ago (skin tissue). This was very exciting—we hoped to learn whether the whales change their habitats or foods throughout their lives.

We analyzed the tissue samples for two stable isotopes: ^{13}C and ^{15}N. ^{13}C is the heavy stable isotope of carbon, and it can help us learn where an animal has been living. ^{15}N is the heavy stable isotope of nitrogen, and it can tell us what foods animals have been eating. When we compared the isotope values between the whales from the east and west Atlantic, we found they were very different (Figure 3B)! This told us that Sowerby's beaked whales on either side of the Atlantic Ocean have different diets. Next, we wanted to know if whales spend their whole lives in one area, or if they move around a lot. We looked at the isotope values in skin, muscle, and bone tissues from the same whales, and we discovered that the whales were staying in the same place and eating the same foods throughout their lives (Figure 3B). Finally,

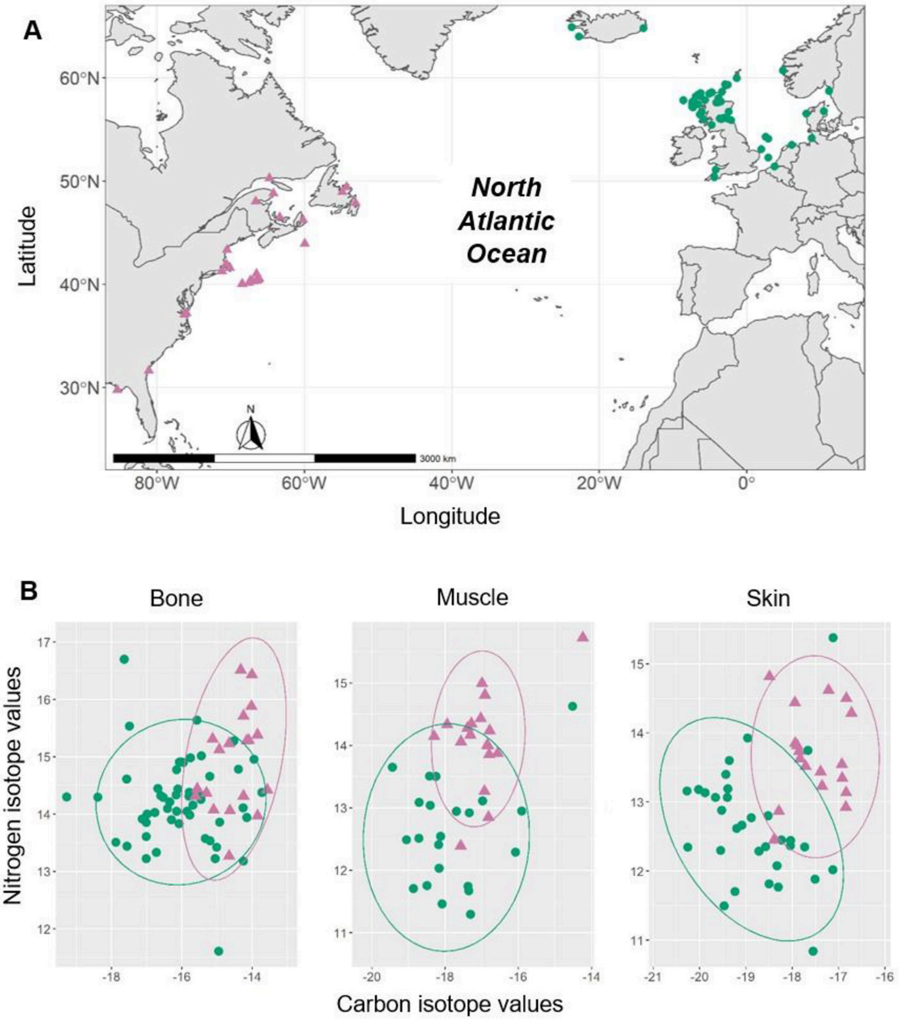


Figure 3

Figure 3

(A) A map of the *North* Atlantic Ocean, showing where the beaked whales in our study were found. Pink triangles show whales from the West Atlantic, and green circles show whales from the east Atlantic. **(B)** Combinations of carbon and nitrogen isotope values for bone, muscle, and skin samples. Circles drawn around the groups of samples, called confidence ellipses, show how similar the combination of isotope values are; if the circles overlap a lot, then the samples have similar values, and if they only overlap a little, then the samples have different values. The circles only partially overlap for all tissue types which, after complicated statistical analyses, tell scientists that the Sowerby's beaked whales have both short- and long-term site fidelity to the region from which the samples were collected. This species is likely composed of at least two populations whose individuals may interact at some point during their lives.

we asked if we could use the isotope values in a whale's tissue to determine where the whale lived, and the answer was yes! The isotope values in whales from the east and West Atlantic were so different that we could correctly say where the whale lived based *only* on its isotope values. Together, these results tell us that Sowerby's beaked whales live in one area their whole lives. We had discovered something completely new about these mysterious animals!

There is still much to learn about Sowerby's beaked whales, but now we know that groups of them live in separate **habitats** and that they do not move back and forth between habitats. This information helps us plan new ways to find and study them so we can learn even more—like the specific foods they eat, if they live in family groups, and how long they live. The information could also help us to conserve these whales. If groups of whales are not moving between habitats, then if one group leaves or dies, beaked whales may be gone from that habitat forever. So, our results are important for people who make policies and rules about ocean noise, pollution, and fishing. Finally, the methods we used

HABITAT

The places where animals and plants live; habitats contain all the resources, like food and water, that animals and plants need to survive and reproduce.

can be repeated for other beaked whale species, helping us to learn more about all these mysterious animals. Maybe now, when you think about whales, you will also imagine beaked whales!

ORIGINAL SOURCE ARTICLE

Smith, K. J., Trueman, C. N., France, C. A. M., Sparks, J. P., Brownlow, A. C., Dähne, M., et al. 2021. Stable isotope analysis of specimens of opportunity reveals ocean-scale site fidelity in an elusive whale species. *Front. Conserv. Sci.* 2:653766. doi: 10.3389/fcosc.2021.653766

REFERENCES

1. Mead, J. G. 2009. "Beaked whales, overview: Ziphiidae," in *Encyclopedia of Marine Mammals (Second Edition)*, eds W. F. Perrin, B. Würsig, and J. G. M. Thewissen (London: Academic Press), p. 94–7. doi: 10.1016/B978-0-12-373553-9.00027-4
2. Madsen, P. T., Aguilar de Soto, N., Tyack, T. L., and Johnson, M. 2014. Beaked whales. *Curr. Biol*. 24:R728–R730.
3. Boecklen, W., Yarnes, C., Cook, B. A., and James, A. C. 2011. On the use of stable isotopes in trophic ecology. *Annu. Rev. Ecol. Evol. Syst.* 42:411–40. doi: 10.1146/annurev-ecolsys-102209-144726

SUBMITTED: 10 November 2021; **ACCEPTED:** 01 June 2023;
PUBLISHED ONLINE: 22 June 2023.

EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Elisa I. Garcordminis

CITATION: Smith KJ, Peterson TR and Peterson MJ (2023) Whale Detectives Use Chemistry Clues to Uncover the Secret Lives of Beaked Whales. Front. Young Minds 11:812844. doi: 10.3389/frym.2023.812844

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

UMBERTO, AGE: 12

My name is Umberto. I like to study science, reading manga and playing videogames with my friends. I love going to the beach to play with sand, have adventures and drawing cartoons. In the future I would like to become a physicist.

AUTHORS

KERRI J. SMITH

I am a wildlife ecologist, and I am interested in increasing our knowledge about animals and ecosystems so we can conserve them. To do this, I work with museums and local communities to get samples from rare animals, then use stable isotopes and genetics to learn more about their lives. I have been studying beaked whales for 6 years, and I want to continue developing new ways to learn about these mysterious animals. *smithkerrij@gmail.com

TARLA RAI PETERSON

I am a science communication professor. I am interested in how we can improve conservation by communicating science. My graduate students and I collaborate with people who want to find better ways to co-exist with the other creatures on Earth. We have worked with communities in Africa, Asia, Europe, and North and South America. We focus on learning from each other and then figure out ways to use our learning to implement conservation initiatives that benefit everyone.

MARKUS J. PETERSON

I am a wildlife ecology and conservation professor. I am interested in developing new ecological knowledge that better informs environmental policy and practice. My graduate students and I study processes that influence wild animal abundance and how this knowledge can help environmental policy makers and conservationists make better decisions. Most of our work takes place on the lands and waters of North, Central, and South America. We also work with local communities in the areas where we conduct our studies.

BIODIVERSITY
Published: 05 May 2023
doi: 10.3389/frym.2023.878138

THE STRESSFUL LIFE OF SEA ICE ALGAE

Zoé L. Forgereau[1*], *Benjamin A. Lange*[2†] and *Karley Campbell*[1]

[1] *Department of Arctic and Marine Biology, Faculty of Biosciences, Fisheries and Economics, UiT The Arctic University, Tromsø, Norway*

[2] *Oceans and Sea Ice, Fram Centre, Norwegian Polar Institute, Tromsø, Norway*

YOUNG REVIEWERS:

SEBASTIAN
AGE: 13

The Arctic Ocean is located at the "top" of the world, and it is covered by sea ice most of the year. It experiences long periods of darkness in winter (polar night) and long periods of light in summer (polar day). During spring and summer, the melting of sea ice decreases the salinity (saltiness) in the upper part of the ocean. These differences in conditions across seasons are called seasonality, and the microscopic algae that live in Arctic sea ice must be able to cope with this strong seasonality. Are you interested in knowing how sea ice algae deal with such extreme changes in their environment? If you are, read this article to discover how sea ice algae adjust to dramatic seasonal variations in both light and salinity.

ARCTIC SEASONALITY

The Arctic Ocean is located at the "top" of the world, and it is covered by sea ice most of the year. Arctic sea ice is subject to strong **seasonality**, which means that it experiences dramatic changes in its environmental conditions across seasons [1]. In winter, Arctic sea ice forms on the ocean surface due to the extremely cold temperatures

SEASONALITY

The differences in environmental conditions (e.g., light, salinity, temperature, and nutrients) which occur across seasons. The Arctic seasonality is specifically extreme as environmental changes happen between winter and summer.

and the long period of darkness during the polar night. The duration of the polar night varies with latitude and can last from November to early March. As the sun returns and the atmosphere warms in the early spring, sea ice is exposed to increasing amounts of light, which causes the snow cover and eventually the sea ice to melt. In late spring and summer, the sea ice faces 24 h of light per day, known as the polar day. As the snow cover and sea ice melt into the ocean, the **salinity** (saltiness) of the ocean's surface water decreases.

SALINITY

The saltiness or the quantity of salt which is dissolved in water. Salt dissolved in water form ion salts, that are either positively or negatively charged atoms (e.g., Na^{+} and Cl^{-}).

SEA ICE ALGAE: THE BASE OF THE ARCTIC FOOD WEB

Tiny photosynthetic microorganisms called **sea ice algae** live in the sea ice, and they are a very important part of the food web of the Arctic Ocean. Table 1 shows some common types of sea ice algae. These algae are mainly found in the bottom of the sea ice, where the ice interacts with the ocean below. Sea ice algae may also live within super-salty pockets of liquid trapped within the ice, called **brine channels**. Sea ice algae are important because they are responsible for **primary production**, which means that they are the first organisms to bring energy into the ecosystem's food web. They do this by creating sugars through photosynthesis, which requires carbon dioxide (CO_2), light energy, water, and nutrients like nitrate, phosphate and silicate [2, 3]. Primary production in the sea ice is therefore controlled by the amount of light and nutrients available, as well as by the temperature and salinity of the algae's environment.

SEA ICE ALGAE

Simple, one-celled photosynthetic organisms that can be classified into several groups, including diatoms (pennate or centric), flagellates, and dinoflagellates.

BRINE CHANNELS

Salty pockets of liquid trapped within the ice in which some algae can grow.

Table 1

Classification of sea ice algae.

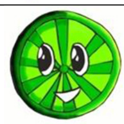
Sea ice algae	Main characteristics	Illustration
Pennate diatoms	Elongated shape with a tough coating of silica.	
Centric diatoms	Circular shape with a tough coating of silica.	
Flagellates	One or more similar flagella (i.e., whip-like structure used to swim).	
Dinoflagellates	Two dissimilar flagella (i.e., whip-like structure used to swim). One looks like a belt around the algae and the other one is hanging down perpendicularly to the first flagellum.	

Table 1

PRIMARY PRODUCTION

The production of sugars by photosynthetic organisms that serve as the base of the food web. In the sea ice environment, algae are the main organisms responsible for primary production.

Major changes in the sea ice environment can stress the algae and reduce primary production, which can affect the entire ecosystem [2]. Sea ice algae are a food source for marine organisms known as zooplankton. Zooplankton are themselves a food source for fishes, which in turn can be eaten by larger organisms like seabirds, seals, polar bears, whales, and even humans! Thus, sea ice algae are the base of the food web in the Arctic ecosystem—which is a major reason why it is important to predict potential changes in primary production that are happening in sea ice. Understanding how sea ice algae survive seasonal environmental changes can help scientists predict how climate change might affect Arctic primary production in the future.

HOW DO SEA ICE ALGAE DEAL WITH LOW LIGHT IN WINTER?

During the Arctic winter, sea ice algae must find ways to survive the dark and cold [1]. They do this by forming structures called cysts (Figure 1A), which are resting stages of an algal cell that have stopped growing to save energy. Cysts have thick walls that help them survive harsh conditions. Diatoms are also known to spend long periods of darkness in a sleep-like state, which allows them to survive for months to even years without light [1].

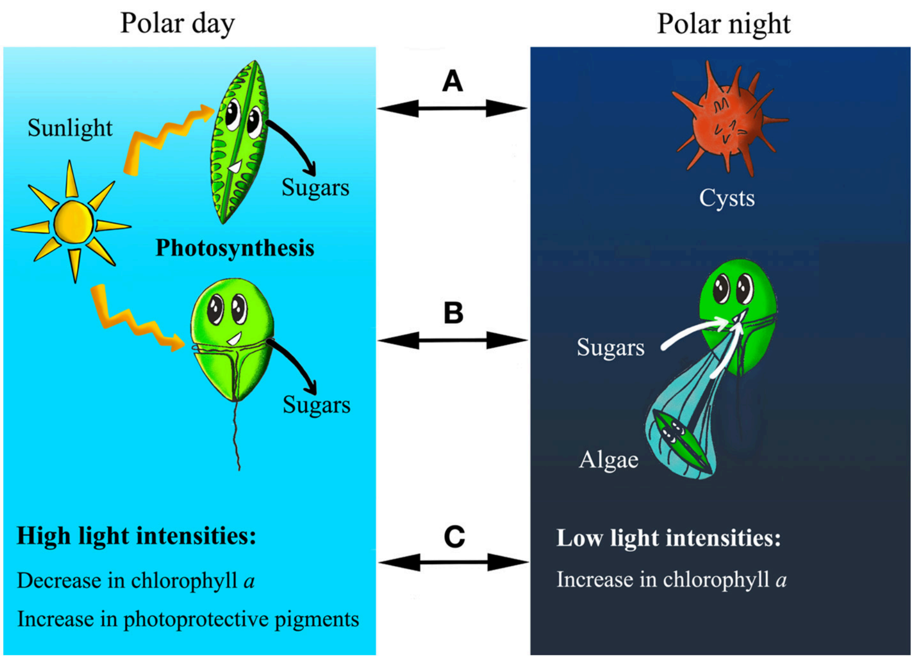


Figure 1

Figure 1

(A) During polar night, sea ice algae produce cysts, which can survive until spring. **(B)** Algae shift their nutrition modes across seasons: during the polar day, they use light to perform photosynthesis; while during the polar night, they feed on sugars or other algae. **(C)** Sea ice algae change the pigments in their cells based on light intensity. They produce more chlorophyll *a* when light is low and decrease its production when light is high. Photoprotective pigments are also produced when light is intense, to protect algae from the harmful effects of light.

Some sea ice algae can also shift nutrition modes to survive the winter (Figure 1B). Most capture sunlight to produce sugars and oxygen *via* **photosynthesis**. For example, diatoms mainly use light to grow and

PHOTOSYNTHESIS

The capture of light, carbon dioxide, water, and nutrients by photosynthetic organisms (e.g., algae and plants) to produce sugars and oxygen.

PIGMENTS

Coloring molecules in cells or tissues. In algal cells, there are photosynthetic pigments, that absorb the light required for photosynthesis, and photoprotective pigments, that protect them from intense light.

survive. But what about when light is not available in the dark of winter? Some sea ice algae can feed on sugars or other algae instead of light, especially when it is dark! This is the case for many flagellates and dinoflagellates.

Sea ice algae can also change the photosynthetic **pigments** within their cells in response to changes in the amount of available light. Photosynthetic pigments are small molecules that absorb the light required for photosynthesis. In the winter, when there is little light available for photosynthesis, sea ice algae tend to increase their production of a photosynthetic pigment called chlorophyll *a*, so that they can absorb more light (Figure 1C) [3].

HOW DO SEA ICE ALGAE DEAL WITH INTENSE LIGHT IN SPRING/SUMMER?

As the sun returns in early spring, the light in the Arctic begins to increase. Through summer, there is an increasing amount of light during the polar day. In early spring, the increase in light allows sea ice algae to grow rapidly, and they become highly abundant. But why? Cysts can germinate as the amount of sunlight increases (Figure 1A), which basically means the sea ice algae wake up! Some sea ice algae may also switch their nutrition mode back to using light as their main energy source (Figure 1B) [1].

In spring and summer, sea ice algae may be exposed to extremely high light intensities due to the melting snow cover that normally prevents sunlight from reaching them. In response, they can produce pigments that protect them from light, called photoprotective pigments. They can also decrease their chlorophyll *a* content to reduce the amount of light they absorb (Figure 1C) [3]. If sea ice algae cannot protect themselves from the extremely high light intensities that occur during the polar day, their rates of photosynthesis may be negatively affected, and they may even die [3]! Some sea ice algae deal with intense light better than others do [4].

HOW DO SEA ICE ALGAE DEAL WITH HIGH SALINITIES IN WINTER?

Sea ice algae are exposed to various salinities depending on where and when they live. For instance, the algae living in the lowest part of the sea ice are subject to normal ocean salinities because they interact with the ocean surface water (Figure 2A) [5], while the algae living in brine channels may face extremely high salinities [5]. Ice algae must have ways to protect themselves from high salinity. When they are exposed to high salinity, the water inside the algal cell will want to move outward into the surrounding seawater or brine, because water naturally tends to move from areas of low salinity to areas of high salinity. In winter, the salty brine and seawater have a higher salinity than the algal cell does, so this can cause the algal cell to shrink as water flows out (Figure 2B) [5].

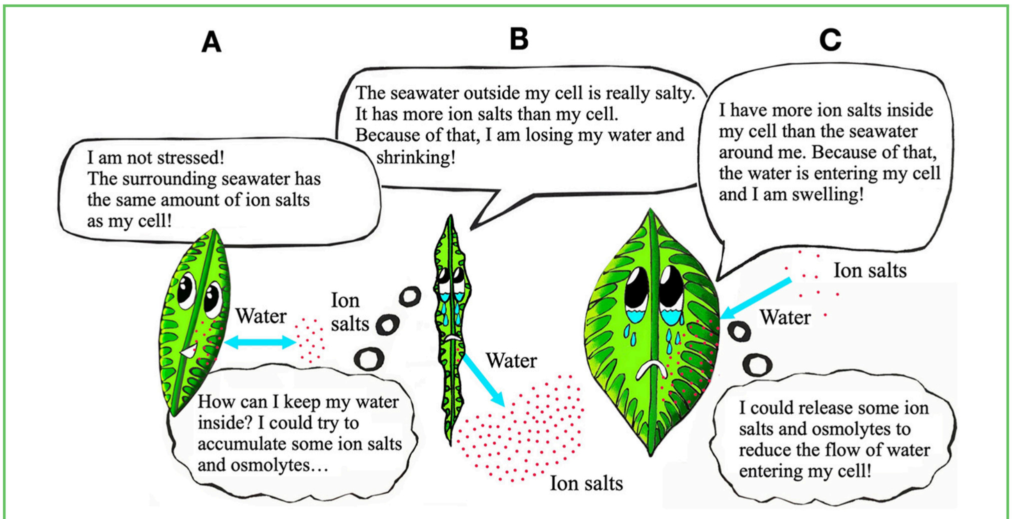


Figure 2

Figure 2

(A) At normal seawater salinities, the algal cell naturally maintains its usual shape. **(B)** At high salinities, the cell shrinks because there is more ion salts outside the cell than inside—so water leaves. **(C)** At low salinities, the cell swells because there is more ion salts inside the cell than outside—so water enters. The blue arrows show the flow of water going into or out of the algal cell. The red dots represent the ion salts.

When salt is dissolved in water, it forms ion salts. High-salinity seawater has a lot of ions, which attract water out of the algal cell. To deal with high salinities, sea ice algae may collect ions within themselves, so that the water stays inside their cells. There are multiple ways to take up ions, some of which require energy and some of which do not [5]. Sea ice algae may also produce substances called **osmolytes**, which are molecules that protect the cell from excessive water flow either into or out of the cell. At high salinities, osmolytes accumulate within the cell to increase the amount of water-retaining substances inside, and therefore contribute to prevent water flow out of the cell [5].

OSMOLYTES

Molecules that protect the cell from excessive water flow either into or out of the cell when it experiences changes in salinity.

HOW DO SEA ICE ALGAE DEAL WITH LOW SALINITIES IN SPRING/SUMMER?

Increasing temperatures in spring and summer cause the snow cover and the sea ice to melt. This adds fresh water to the salty ocean and brine channels, which decreases their salinity. When sea ice algae are exposed to low salinities, the concentration of salt inside their cells is higher than that outside their cells. Therefore, the surrounding water tends to enter algal cells, causing them to swell (Figure 2C). This is the opposite of what happens when algal cells are exposed to high salinities. Thus, when salinities are low, algae must have ways to reduce the flow of water entering the cell. To deal with low salinities, sea ice algae can release ions. Similar to the process of collecting ions, some methods of ion release require energy while others do not. Flagellates and sea ice diatoms may also release osmolytes to prevent water from entering their cells, as these are water-retaining substances [5].

Some sea ice algae can adjust to low salinities better than others can. Pennate diatoms—elongated cells with a tough coating of silica—are often the best at adjusting to dark, salty winter conditions (Figure 3A) [4]. On the other hand, flagellates—cells with one or more similar flagella (i.e., whip-like structure used to swim)—and centric diatoms—circular shape cells with a tough coating of silica—often adjust better to low salinities than pennate diatoms do [4]. As a result, pennate diatoms are the first algae to be lost from the bottom-ice during melting in late spring, while other groups thrive like flagellates and dinoflagellates—cells with two dissimilar flagella, one looks like a belt around the cell and the other flagellum hangs down, perpendicular to the first (Figure 3B). Flagellates and dinoflagellates tend to dominate in late spring-summer because flagellates typically adjust better than diatoms to low salinities and reduced nutrients (Figure 3C) [4].

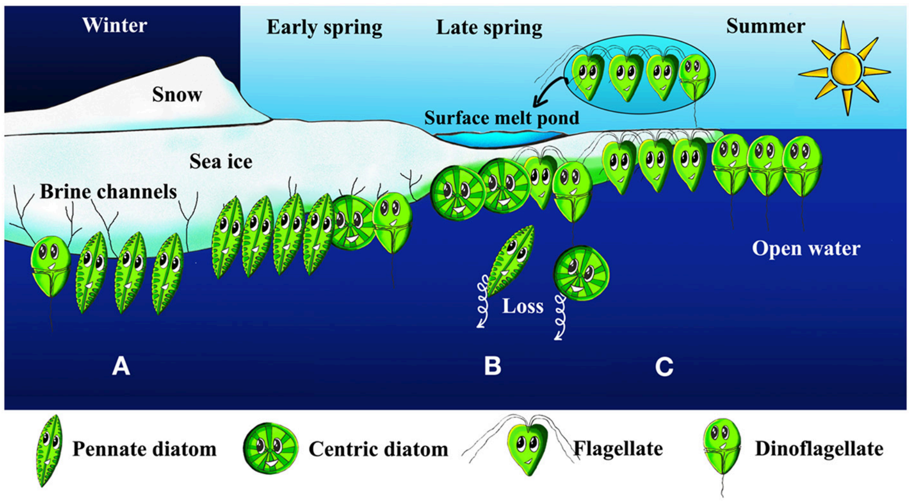


Figure 3

Changes in salinity across seasons favor the growth of different types of sea ice algae. **(A)** Pennate diatoms are often the best at adjusting to the high salinities in the dark, cold winter. They also typically dominate the bottom-ice in early spring. **(B)** Centric diatoms, flagellates, and dinoflagellates adjust best to the low salinities in late spring. **(C)** Flagellates and dinoflagellates adjust best to the low salinities and limited nutrients in late spring/summer.

KEY MESSAGES

Arctic sea ice is subject to strong seasonal changes, as it undergoes extended periods of darkness (polar night) and daylight (polar day). Tiny, photosynthetic sea ice algae living in this environment must adjust to cope with extreme seasonal changes in light intensity and salinity. To do so, they can form cysts, shift their nutrition modes, regulate their internal pigment content, and change their ion salt and osmolyte concentrations. Various types of sea ice algae may adjust differently to Arctic seasonality. Pennate diatoms typically adjust better to the dark, highly saline winter conditions; while centric diatoms and especially flagellates are believed to grow better in the warmer, less salty conditions of late spring and summer. Sea ice algae form the base of the Arctic food web, which is why it is important to predict potential changes in sea ice primary production. Scientists are currently trying to understand how Arctic sea ice algae survive seasonal environmental changes to better predict how climate change could affect Arctic sea ice primary production in the future.

ACKNOWLEDGMENTS

This work was written as a part of an individual science communication course at UiT The Arctic University of Norway and was a contribution to the Diatom-ARCTIC (Diatom Autoecological Responses with Changes To Ice Cover) project funded by the NERC Science of the Environment (NE/R012849/1; 03F0810A), the Fram Centre Flagship-funded project PHOTA (Physical drivers of ice algal HOTspots in a changing Arctic Ocean, Tromsø, Norway, # 66014, PI: BL), as well as to the Research Council of Norway funded projects BREATHE (Bottom sea ice Respiration and nutrient Exchanges Assessed for THE Arctic, grant no. 325405, PI: KC), CAATEX (grant no. 280531), and HAVOC (grant no. 280292). This work was also supported by the Research Council of Norway through the Arctic Field Grant (AFG # 322575 to ZF).

REFERENCES

1. Berge, J., Johnsen, G., and Cohen, J. H. 2020. *POLAR NIGHT Marine Ecology: Life and Light in the Dead of Night*. Berlin: Springer Nature.
2. Thomas, D. N. 2017. *Sea Ice*. Hoboken, NJ: John Wiley & Sons.
3. Falkowski, P. G., and Raven, J. A. 2013. *Aquatic Photosynthesis*. Princeton, NJ: Princeton University Press.
4. Van Leeuwe, M. A., Tedesco, L., Arrigo, K. R., Assmy, P., Campbell, K., Meiners, K. M., et al. 2018. Microalgal community structure and primary production in Arctic and Antarctic sea ice: A synthesis. *Elementa* 6:e267. doi: 10.1525/elementa.267
5. Kirst, G. 1990. Salinity tolerance of eukaryotic marine algae. *Ann. Rev. Plant Biol*. 41:21–53. doi: 10.1146/annurev.pp.41060190.000321

SUBMITTED: 17 February 2022; **ACCEPTED:** 13 April 2023;
PUBLISHED ONLINE: 05 May 2023.

EDITOR: Sanae Chiba, North Pacific Marine Science Organization, Canada

SCIENCE MENTORS: Luisa I. Falcon

CITATION: Forgereau ZL, Lange BA and Campbell K (2023) The Stressful Life of Sea Ice Algae. Front. Young Minds 11:878138. doi: 10.3389/frym.2023.878138

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

SEBASTIAN, AGE: 13

I like sports, reading, math, physics, and all things space!

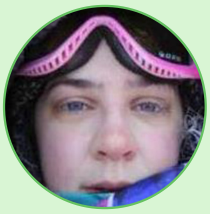
AUTHORS

ZOÉ L. FORGEREAU

Zoé L. Forgereau completed a Master of Science in Marine Ecology and Resource Biology at UiT, The Arctic University of Norway. She investigated the photosynthetic responses and primary production of sea ice algae when dealing with decreases in salinity. For her master's project, she conducted a field-based study on bottom-ice algae in Svalbard, and carried out lab-based experiments. *zoe.figaro@orange.fr

BENJAMIN A. LANGE

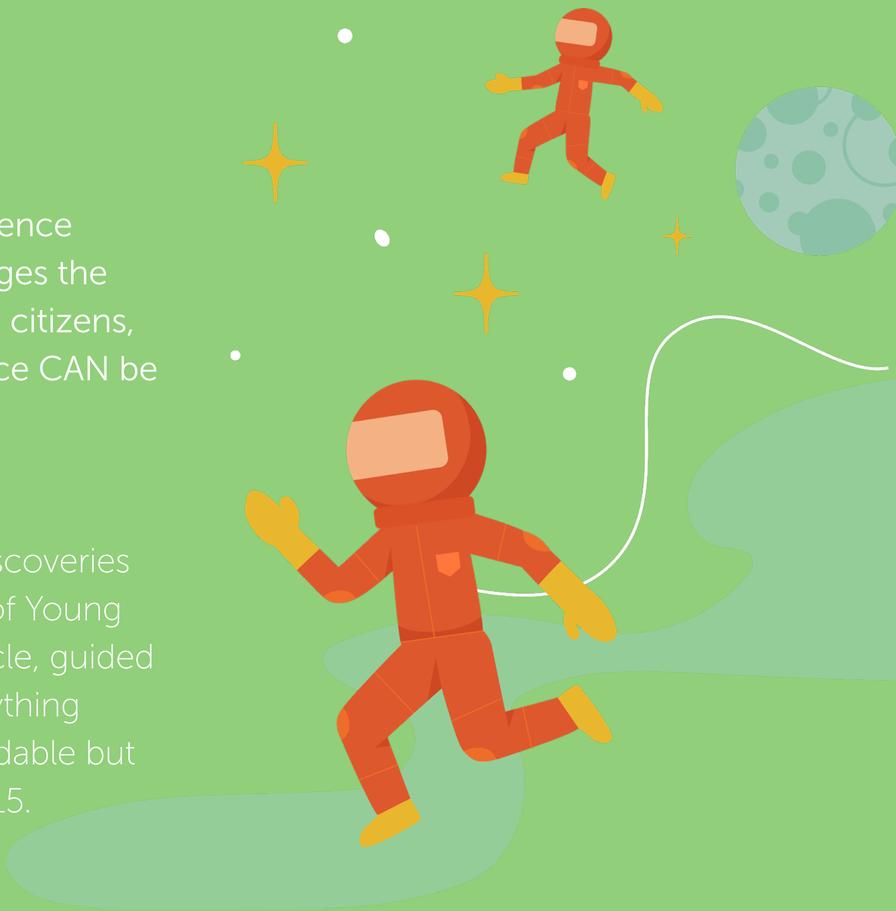
Benjamin A. Lange is currently working at the Norwegian Geotechnical Institute as a Remote Sensing Scientist. His main research interest is in mapping marine and coastal habitat properties and suitability using various approaches, such as ice coring and drilling, underwater robotic systems (e.g., remotely operated vehicles), and airborne and satellite remote sensing (e.g., drones). †Remote Sensing and Geophysics, Norwegian Geotechnical Institute, Oslo, Noway



KARLEY CAMPBELL

Karley Campbell is an Associate Professor of Marine Botany at UiT, The Arctic University of Norway and an affiliated researcher at the University of Manitoba, Canada. She conducts lab and field-based studies on sea ice microorganisms to see how they live now, and how they could live in the future with climate change.

Frontiers for Young Minds



Our Mission

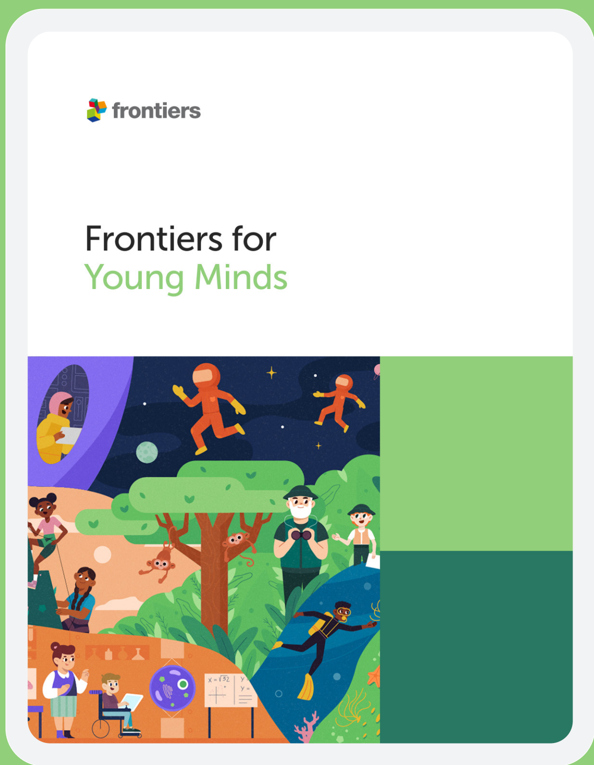
To publish high-quality, clear science which inspires and directly engages the next generation of scientists and citizens, sharing the revelation that science CAN be accessible for all.

How we do this?

Top researchers write up their discoveries for kids and our global network of Young Reviewers peer review every article, guided by their mentors, to ensure everything we publish is not only understandable but engaging for their peers aged 8-15.

Discover our latest Collections

See more →



Social Media

@FrontYoungMinds
@FrontiersForYoungMinds
@frontiersyoungminds
#frontiersforyoungminds

Contact us

+41 21 510 1788
kids@frontiersin.org