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The Ocean, Volume 1

Edited by
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Sanae Chiba and Emily King

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The Ocean, Volume 1

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Biodiversity

Earth and its Resources

About this collection

The ocean was the origin of life on earth billions of years ago and it is vital for the future of humanity. It is vast, deep, harsh and somehow “rebellious” to uncover its secrets and hence, there is much that is unexplored and misunderstood. Scientists need to study the ocean to better understand its functioning and properties, as well as how they shape our environment and impact us. For example, do you know what the role of the ocean is on weather and climate? There still remains so much to explore in ocean biodiversity and the diverse resources that can be found (for example, fish stocks, bio-molecules, and also minerals, oil, and gas). How can we make sure that our use of these resources is done sustainably and how can we minimize our impacts (e.g. pollution, acidification) on the ocean as our human population increases?

In this collection of Frontiers for Young Minds, scientists from various disciplines in oceanography share their knowledge and motivations, give insights in innovative tools and recent discoveries to better understand this ocean. The collection will target a large range of oceanic environments from the open ocean to the coast, the surface to the abysses also including specific areas like coral reefs or sea-ice environments. It will cover marine disciplines that range from physics to chemistry, from biology to ecology and from economy to conservation and policies. It will address innovative tools and methods that are used to observe and characterize oceanic properties and features: ships and satellites, the highly diverse variety of robots as well as genomics or artificial intelligence. Finally, it will encompass a great variety of scales, ranging from the diel to geological time-scales and 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. This Ocean collection aims 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.

Table of contents

frontiers FOR YOUNG MINDS

BIODIVERSITY
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SHARING ELECTRONS: AN EXTRAORDINARY FRIENDSHIP BETWEEN BACTERIA

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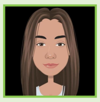
YOUNG REVIEWERS:

MARIANA
AGE: 15



ZARA
AGE: 14

Did you know that iron is one of the most important elements on Earth? It is assumed that life evolved close to iron sources. This means that the earliest life forms—and therefore oldest creatures—were able to use iron to obtain energy the way we use food. These tiny organisms are called iron microorganisms and can occur in sediments, which are mainly muddy sand. But less was known about where iron microorganisms live in these sediments—are they located close to the water surface or deep in the sediment? In this study, a team from the University of Tübingen investigated the distribution and variety of iron microorganisms. The scientists discovered that iron microorganisms live independent from their favorite foods: iron, oxygen, and light! This independence might be explained by an unexpected extraordinary friendship with a "living cable." Are you curious about what a living cable is?

DID YOU KNOW THAT SOME BACTERIA CAN "EAT" IRON?!

Microorganisms are microscopic life forms that include bacteria, archaea, fungi, algae, protozoa, and viruses. In this study, I focused on bacteria. Bacteria live in our stomachs and on our skin, but also live everywhere else: from the deepest parts of the Earth's crust to high up in the clouds, and they even manage to live under the ice of the Antarctic or in hot springs. One teaspoonful of **marine sediment** contains more than a billion bacteria! Although bacteria are so small, there are so many of them that they have a huge impact on our environment.

MARINE SEDIMENT

Rock and soil particles transported from coastal areas into the ocean by wind, ice, and rivers, as well as the remains of marine organisms.

To survive in such diverse environments, species of bacteria have evolved to "eat" many different things to obtain the energy they need to survive. The ones I will focus on in this article like iron! Iron bacteria are widespread in our environment. After oxygen, silicon, and aluminum, iron is one of the most common elements on Earth. Iron bacteria were essential for the beginning of life on Earth and might also be important on other iron-containing planets, such as Mars.

Iron bacteria can use iron to generate energy for their growth, and in doing so they produce waste products in the form of brownish iron minerals [1], commonly known as rust. So far, three groups of iron bacteria have been found to form iron minerals. One group is light-dependent, meaning they need light to survive, the second group is oxygen-dependent, and the third group is nitrogen-dependent [1].

GEOCHEMICAL GRADIENT

The difference between two compartments (upper and deeper sediment layers, in our case) in relation to the amount of substance like oxygen or light, or the temperature, pressure, or salt concentration.

Some iron bacteria live in coastal sediments, which are mainly muddy sand. Typical coastal sediment is usually made up of layers following **geochemical gradients** [2] (Figure 1). In the upper sediment layers that can be reached by sunlight, oxygen, and a lot of organic substances can be detected. In the deeper sediment layers there is less light and oxygen, but it is still possible to measure a bit of nitrate, organic substances, iron, iron minerals, and sulfate. These specific layers are mainly formed by the food preferences of the different sediment bacteria present at each sediment layer.

CELLULAR RESPIRATION

The process that all living organisms use to create the energy they need to live. It involves the transfer of electrons from an electron donor (high energetic compound) to an electron acceptor (less energetic compound), resulting in the release of energy.

HOW DO BACTERIA GET ENERGY FROM FOOD?

To explain my research findings, we first need to go into a little more detail about the process by which bacteria get energy from their chosen food. At the cellular level, the process that all living things, including bacteria, go through to generate the energy they need to grow is called **cellular respiration**. At the smallest molecular level, this involves the exchange of electrons, which are the small pieces of an atom that have a negative electrical charge. In principle,

Figure 1

Geochemical gradients in marine sediments. The layered structure of typical coastal sediments is shown with an actual sediment core containing marine coastal sediment from the Danish coast (Norsminde Fjord, Denmark) is shown in the center. The upper layer is brownish from the organic food and the deeper layer is blackish from the iron minerals. The presence of electron acceptors and electron donors in the sediment layers is shown on the left and right of the core, with the general location of various substances in the gradient indicated by the colored bars. In the upper layers of the sediment, light-, oxygen-, and organic food-dependent reactions take place, while further down in the sediment, the processes depend on nitrate, iron, and iron minerals. e⁻, electrons; O_2, oxygen.

ELECTRON DONOR

A chemical substance that releases electrons to other compounds during a half reaction of cellular respiration. For example: organic substances or iron.

ELECTRON ACCEPTOR

A chemical substance that accepts electrons transferred to it from another compound during a half reaction of cellular respiration. For example: oxygen, nitrate, sulfate, iron minerals.

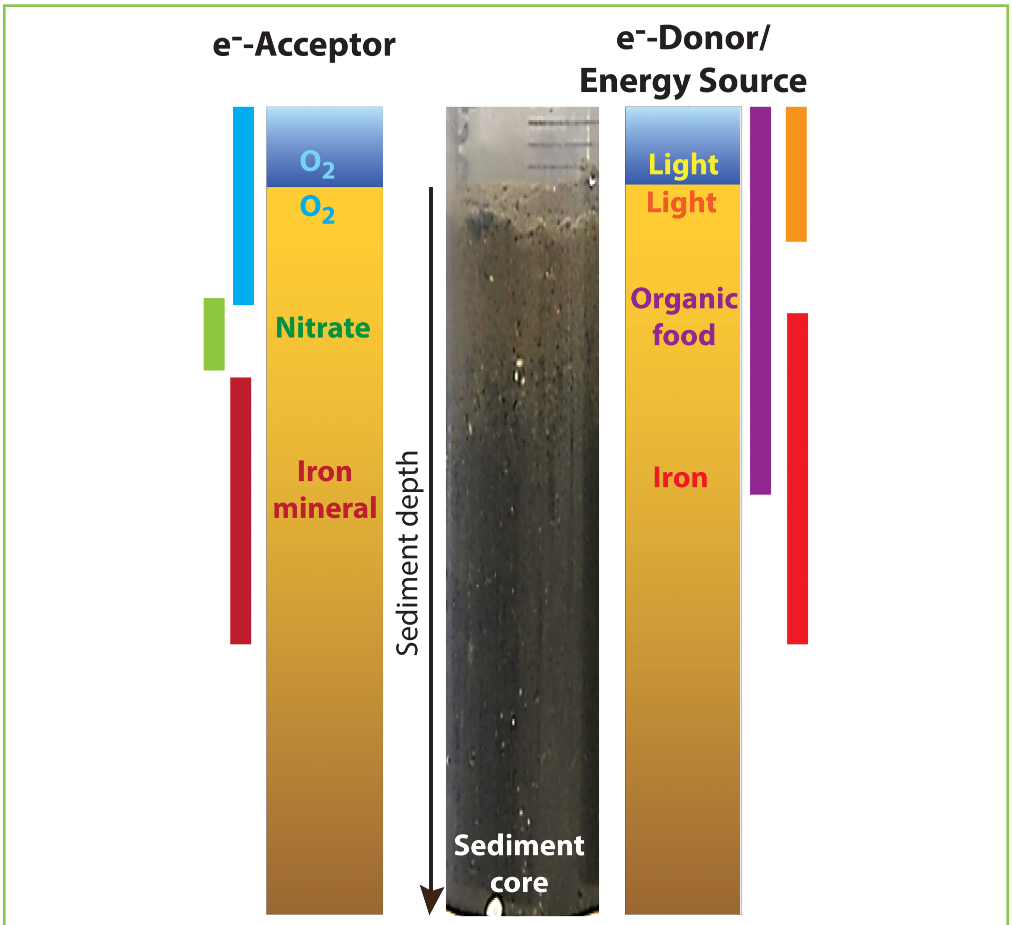


Figure 1

one food source for bacteria is what is called an **electron donor** (it donates electrons) and another source called the **electron acceptor** (it accepts electrons). While typical electron donors in sediments are soluble iron or organic substances from, e.g., dead organisms, typical electron acceptors are oxygen, nitrate, or iron minerals (Figure 1). The degradation of organic substances using oxygen provides the highest amount of energy and, as a result, oxygen is typically used up first, followed by nitrate, and then iron minerals [2].

So far, we know that iron bacteria—and all other organisms—need an electron transfer reaction to gain energy. Iron bacteria receive electrons from iron (the electron donor) and give the electrons to oxygen (the electron acceptor) [1]. In summary, this electron transfer from iron to oxygen allows the bacteria to receive energy for cell growth. This shows that bacteria are really smart: they use the energy differences of the electrons in iron (high potential) and in oxygen (low potential) to generate energy. You can compare it with a natural waterfall and a hydropower plant. The electrons from iron with a high energy potential fall down to oxygen with a lower energy potential (like a waterfall). During this process the iron bacteria can run their turbines (like in a hydropower plant) and produce energy. For iron-bacteria the electron transfer occurs at the cell membrane, where they produce

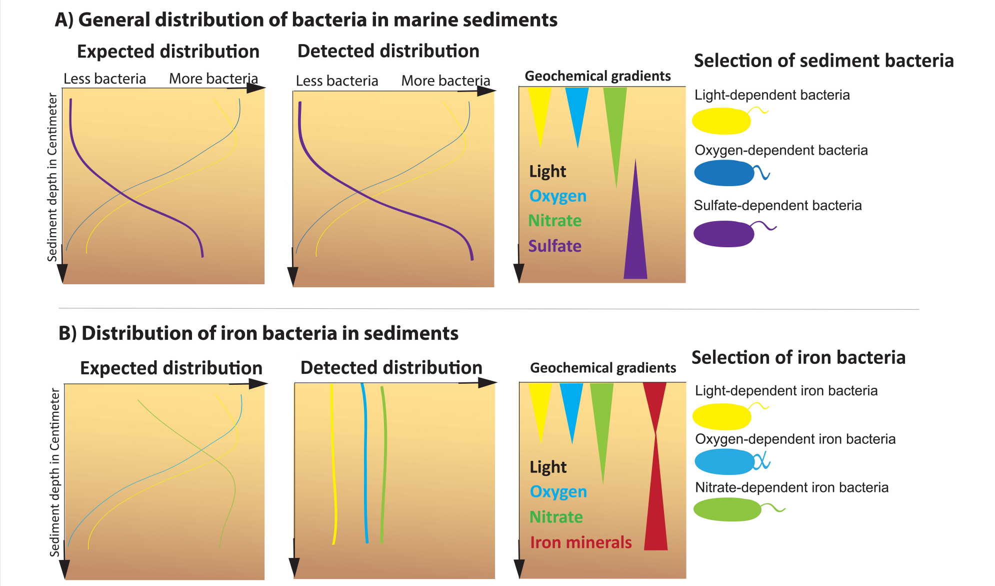


Figure 2

Figure 2

The expected and measured distributions of bacteria in coastal sediments. **(A)** We expected that, when we looked at all typical sediment bacteria, we would see the different types of bacteria (shown on the right) distributed according to the gradients of substances they need to create energy (e.g., light, oxygen, and sulfate). The panel labeled "geochemical gradients" shows the amounts of the indicated substances as triangles, with the wide part representing a greater concentration of the substance and the narrowing of the triangle showing decreasing concentration. We detected that about 75% of the bacteria are orientated according to the gradients. When a huge amount of oxygen is available a lot of oxygen-dependent bacteria can be found, when less oxygen is present almost no oxygen-dependent bacteria is detectable. **(B)** When we looked at just the three types of iron bacteria, however, we found that they do not follow the expected distribution in the sediment and instead are found throughout all the sediment layers.

the iron minerals. It is important to mention that the cell membrane of iron bacteria is equipped with a special biochemical machinery (called wires) to transport electrons along their cell membranes [3]. Of course, the electron transfer reaction of iron bacteria is much more complex and therefore different in comparison to other sediment bacteria and other organisms.

UNEXPECTED DISTRIBUTION OF IRON BACTERIA IN COASTAL SEDIMENTS

Until recently, the natural distribution of iron bacteria in the layers of coastal sediments was unknown. Therefore, equipped with rubber boots, gloves, buckets, bottles, and syringes, a research team from the University of Tübingen spent 3 years collecting various sediment samples in Denmark on the Baltic Sea coast to study the distribution of iron bacteria in typical coastal sediment. They analyzed the types of bacteria in the samples and the amounts of iron, oxygen, and nitrate that were present in the upper few centimeters (0–5 cm) of the sediment. At the surface layer of the sediment, I detected oxygen which decreased within the deeper sediment layers [4] (Figure 2A). I expected to see that this oxygen gradient also determined the types of bacteria living in all sediment layers. Then, we looked for all typical sediment bacteria that are dependent on light and oxygen. Most of the light- and oxygen-dependent sediment bacteria were found living at the surface and less of them living in the deeper sediments, which is what my colleagues and me expected [4] (Figure 2A).

However, when specifically looking at all three types of iron bacteria, even those that were dependent on substances present in the surface layers of sediment like oxygen, nitrate, and sun light, my colleagues

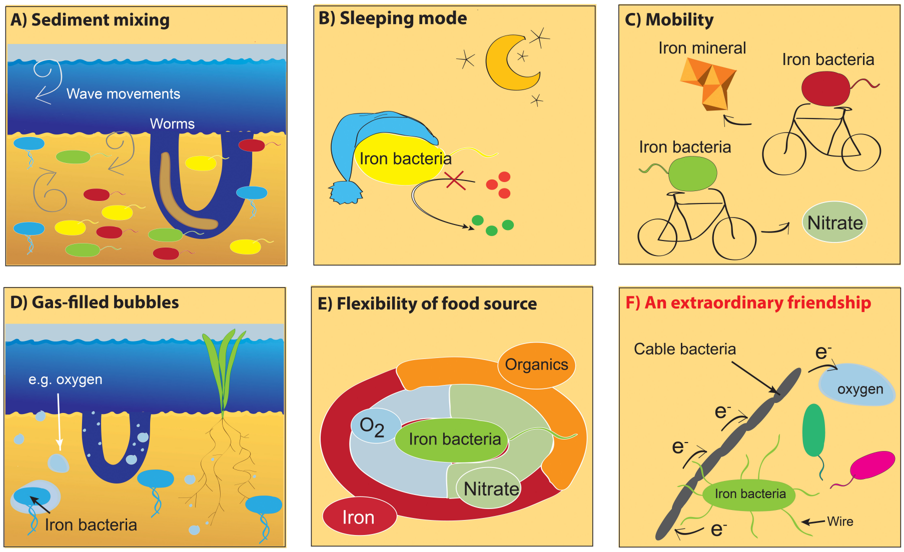


Figure 3

Why are iron bacteria distributed through all sediment layers? We explored several possible reasons why iron bacteria do not follow gradients in the sediment. **(A)** Physical mixing by waves or worms; **(B)** iron bacteria are "sleeping" and do not need nutrients; **(C)** iron bacteria can move throughout the layers; **(D)** iron bacteria find small bubbles filled with oxygen or nitrate; **(E)** iron bacteria can eat various "foods"; and **(F)** iron bacteria interact with cable bacteria which help them to exchange electrons. None of the explanations from **(A)** to **(E)** could explain the distribution. Instead, we suggest that iron bacteria can use the cable bacteria as, e.g., electron acceptors. This allows the iron bacteria to live independent from the geochemical gradients of, e.g., oxygen, thanks to the help of their friends—the cable bacteria. e^-, electrons; O_2, oxygen.

and me were really surprised to find all three types of iron bacteria were equally mixed through all the sediment layers [4] (Figure 2B). This means that iron bacteria behave differently than most of the sediment bacteria and do not orient themselves according to the gradients of oxygen, nitrate, or sun light when choosing their favorite spot to live. Since this was a very interesting result, I tried to figure out why iron bacteria behave differently than other types of bacteria and can live in all sediment layers.

HOW CAN WE EXPLAIN THE UNEXPECTED DISTRIBUTION OF IRON BACTERIA IN SEDIMENTS?

Several hypotheses could explain the distribution of iron bacteria throughout the layers of sediment (Figures 3A–E).

(A) *Might the iron bacteria become mixed through the sediment layers by worm activity or wave movements?* My colleagues and I are not inclined toward this hypothesis because mixing should affect all sediment bacteria, so this does not explain why only iron bacteria were found throughout all layers.

(B) *Might the iron bacteria be in a kind of "sleep" state in some of the layers, resting until better conditions are available?* However, the iron bacteria were really active and were not "sleeping," so this hypothesis cannot explain the distribution pattern of bacteria across the sediment.

(C) *Maybe the iron bacteria are mobile, and able to travel through the sediment layers?* The ability to move is not a special feature of iron bacteria; although a lot of sediment community members are mobile.

(D) *Can iron bacteria use oxygen- or nitrate-filled "bubbles" in deeper sediment layers as a food source?* The small, gas-filled bubbles of oxygen or other food sources could not explain the distribution of iron bacteria alone. So, this hypothesis was also ruled out.

(E) *Are iron bacteria flexible with their food source?* Again, a flexible diet could not explain the distribution of all the different iron bacteria along the sediment alone.

When realizing that the behavior of the iron bacteria could not be explained with any of these hypotheses, my colleagues and I had to continue their research. And it became more and more exciting!

DO THE FASCINATING ELECTRIC CABLE BACTERIA PLAY A ROLE HERE?

In 2010, a team of scientists from the Center for Electromicrobiology in Denmark discovered unusual electric bacteria [5] which have a multicellular structure containing thousands of cells in line. These extraordinary bacteria are called cable bacteria. In contrast to other bacteria, cable bacteria can transport electrons over long distances (around 5 cm!) in their multicellular cable and function like electric cables in the sediments! So, the hypothesis to explain the distribution of iron bacteria along the sediment might rely on the electric cable bacteria. Indeed, cable bacteria and iron bacteria were living together in the same sediment layers [4] (Figure 3F). Why is it an extraordinary friendship? Remember that iron bacteria need an electron transfer reaction to gain energy and that iron bacteria are equipped with special biochemical machinery (also called wires) on their cell membranes that helps them to provide or grab electrons [3]. Using this biochemical machinery, iron bacteria can transfer electrons to the cable bacteria when they do not have oxygen available as an electron acceptor! The cable bacteria can act as an electron acceptor for iron bacteria, picking up the electrons from the iron bacteria and moving them through the cable to the sediment surface. At the sediment surface, there is a lot of oxygen that can act as a normal electron acceptor. Thanks to the extraordinary friendship with cable bacteria, oxygen-breathing iron bacteria can thus survive in all sediment layers, independent of oxygen being present in the sediment layer where they live and use the cable bacteria as a kind of a snorkel! Nitrate- and light-dependent iron bacteria can also live independent of their food sources in all sediment layers (Figure 3B), possibly using the same mechanism.

AN EXTRAORDINARY MICROBIAL FRIENDSHIP

The relationship between iron bacteria and cable bacteria needs more evidence to confirm this extraordinary friendship. However, with this study my colleagues and I already showed that iron bacteria are likely using a unique strategy to survive in all sediment layers, independently of their vital food source being present! Iron bacteria use their special ability to transport electrons on their cell membranes—which is not the case in most other bacteria—and they can interact with the cable bacteria. So, the extraordinary friendship of iron bacteria and cable bacteria could explain the special distribution of iron bacteria in marine sediments. The surprising bacterial distribution and unexpected relationship of the iron bacteria and cable bacteria throughout all sediment layers also has a positive effect on the entire microbial community, since the iron bacteria can live in deeper sediment layers independent of, e.g., light and oxygen and can help other organisms with the production of their iron minerals. For example, toxic substances can stick to iron minerals and are no longer harmful for others. In this way, the extraordinary bacterial friendship can have a number of other positive side effects on the ecosystem. Of course, further research is needed to understand the exact relationships between the two friends. Scientists learned that cooperation, even at the small scale of bacteria, can help organisms to survive. This type of positive interactions, when both bacterial groups gain something when working together, occurs through the tree of life.

ORIGINAL SOURCE ARTICLE

Otte, J. M., Harter, J., Laufer, K., Blackwell, N., Kappler, A., and Kleindienst, S. 2018. The distribution of active iron cycling bacteria in marine and freshwater sediments is decoupled from geochemical gradients. *Environ. Microbiol.* 20:2483–99. doi: 10.1111/1462-2920.14260

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YOUNG REVIEWERS

MARIANA, AGE: 15
Hi! My name is Mariana and I am 15 years old. I like reading books, spending time with animals, and swimming. I consider every day brings an opportunity for me to learn something new and for being happy.

ZARA, AGE: 14
My name is Zara and I am 14 years old. In my spare time, I enjoy reading, helping my community, and playing volleyball. I think it is important to work hard for achieving our dreams and for being a better person every day.

AUTHOR

JULIA M. OTTE
I was trained in Bio Science and Geo Science at the University of Heidelberg (Germany) and the University of Freiburg (Germany), with a specialization in Molecular Biology, Biochemistry, and Microbiology. In 2018, I finished my Ph.D. at the University of Tübingen (Germany) with a specialization in Geomicrobiology and Microbial Ecology, with a focus on iron-cycling bacteria in marine sediments. Since 2018, I have been in the HGF-MPG Group for Deep-Sea Ecology and Technology at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Bremerhaven and at the Max Planck Institute for Marine Microbiology in Bremen (Germany). I am currently working on the impacts of deep-sea mining in the Pacific Ocean on metal-cycling microorganisms on the 4,000 m deep seafloor. *julia.otte@awi.de; jotte@mpi-bremen.de

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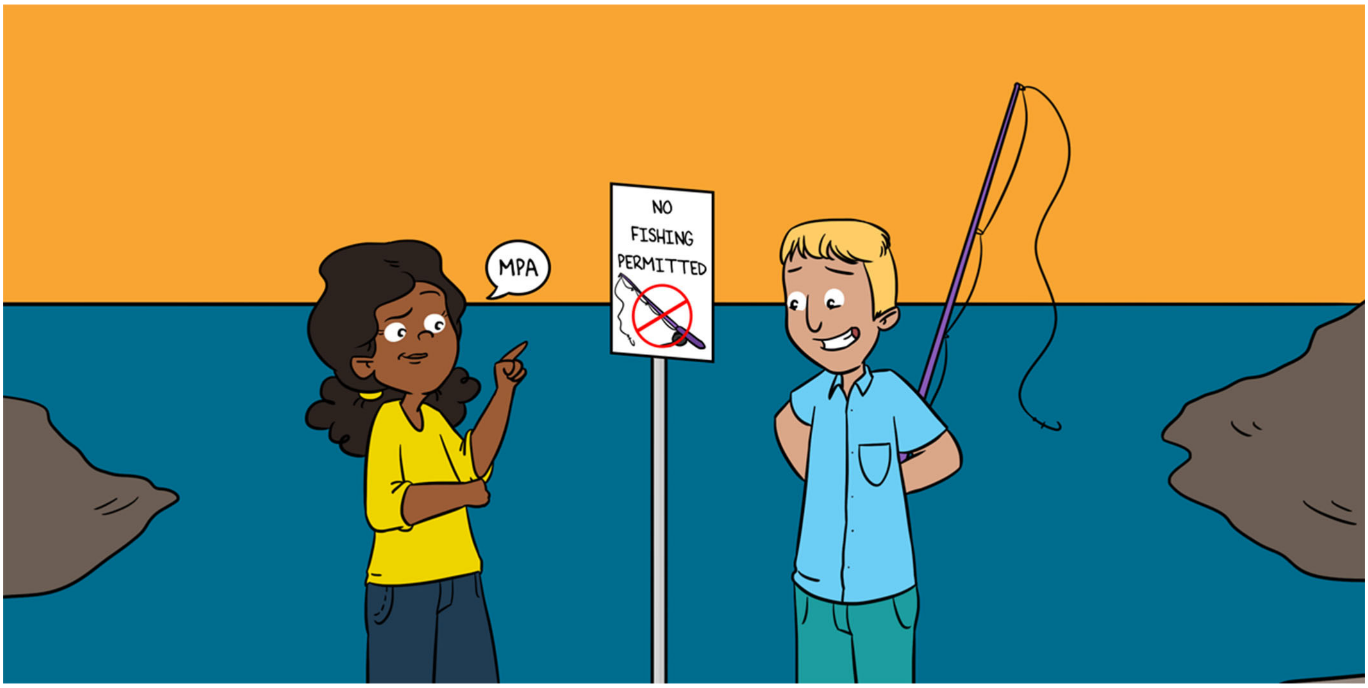

MARINE PROTECTED AREAS: A WAY TO PROTECT OUR OCEANS

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YOUNG REVIEWER:

LUANA
AGE: 15

Have you ever walked around a forest or park, and noticed signs saying things like: "Do not Pick Flowers" or "Do not Feed the Animals"? These signs indicate that the area you are in is being protected from humans. When these protected spaces are in the ocean, they are called marine protected areas. Marine protected areas vary in type, from heavily protected areas, to areas where visitors can use the ocean for recreation. Special rules and regulations protect and conserve underwater habitats, plants, and animals in these areas. Marine protected areas exist all over the world and can result in more and bigger fish, which can lead to a healthier ocean. While it is not easy to create such an area, local community groups, single countries, and even big groups of countries have worked to create marine protected areas, ensuring that their oceans are protected and healthy.

WHAT ARE MARINE PROTECTED AREAS?

Have you ever gone to a forest that has special rules in place, like maybe a rule that you cannot pick flowers? These rules are meant to protect the plants and animals in the forest. Just like on land, special rules can exist for parts of the ocean, too. They are called **marine protected areas** (MPAs), and they are areas that may protect habitats, species, or ecosystems [1]. MPAs might also protect areas that have special significance to a culture or a religion [1]. Just like parks on land, an MPA needs to be managed with rules, such as whether fishing is allowed, or how many fish can be caught. There are not any rules about size—an MPA can be small or really big; some are larger than a football field [1, 2]!

TYPES OF MARINE PROTECTED AREAS

There is not just one type of MPA. Rather, there is a long list of types that allow communities to choose what MPA type fits best with their needs. The International Union for Conservation of Nature (IUCN) lists six types of MPAs. Each MPA has a different description and goal (Table 1). For example, MPAs classed as category 1A are strictly protected to preserve **biodiversity** while limiting how humans use the space; they are often called "no take zones," because only researchers are allowed inside them, and only if they have gotten permission from the managers of the MPA. The 11 marine reserves within the USA's Channel Islands National Marine Sanctuary fall within this category (Figure 1). Similarly, category 3 MPAs allow for the protection of the amazing natural wonders that the ocean houses. For example, the Blue Hole Natural Monument in Belize features a circular, deep underwater sinkhole (Figure 1). This is a rare feature and its surrounding ecosystem is protected as a category 3 MPA [1].

BIODIVERSITY

All types of life, such as plants, animals, and fungi, as well as the habitats they live in.

Almost all categories focus on the marine area as a whole, from habitats, to plants, to species. This changes with a category 4 MPA. The goal of a category 4 MPA is to protect something specific, such as a species of seabird, or sea turtles, or mangrove forests. The South Ari Atoll MPA in the Maldives, e.g., was created to protect and conserve whale sharks that are native to their waters (Figure 1) [1]. Researchers recognize that humans have long relied on the ocean for food or for sport. Category 5 MPAs look to protect the ocean that has value to a community. For example, Apo Island in the Philippines allows for tourism that does not harm the environment and for locals to use the ocean through **traditional management** (Figure 1) [1]. Lastly, there is category 6. This type of MPA allows both conservation and **sustainable use**. This means that, in addition to protecting species and habitats, humans can use the ocean (they can fish or sail), if it is done in way that does not harm biodiversity.

TRADITIONAL MANAGEMENT

A type of resource management that is rooted in local traditions, history, and ecological knowledge.

SUSTAINABLE USE

Making sure to not catch so many fish that there are not enough fish for future generations.

Table 1

International Union for Conservation of Nature (IUCN) descriptions of categories of marine protected areas and their goals. Adapted from Day et al. [1].

Category number	Description	Main goal
1A	Strictly protected areas that look to preserve biodiversity and geologic features. Human impact, such as through visiting or fishing, is strictly controlled and limited.	To conserve ecosystems, species, and/or geological features.
1B	An area that is protected and managed to conserve biodiversity. The area may have been slightly modified by humans but does not have humans living within the area.	To protect areas that are undisturbed by significant human activity, so that future generations can experience the area in its natural form.
2	Areas that protect the ecosystem while allowing humans to use the land, such as through recreation or education.	To protect biodiversity while promoting education and recreation.
3	Areas that protect a specific natural feature.	To protect natural features and their surrounding biodiversity and ecosystems.
4	Areas that protect a specific species or habitat.	To protect, conserve, and restore species and habitats.
5	Areas with a long history of humans using the natural space.	To protect and sustain the marine environment, and to allow humans to use and manage the space through traditional practices.
6	To protect ecosystems and their resources, while encouraging sustainable use.	To balance conservation and sustainable use of the area.

Table 1

Figure 1

Map of Global MPAs. The dark blue represents where MPAs are present on our Earth. MPAs mentioned in this article are highlighted by the compass icons in the legend. Due to the map projection, the Ross Sea is labeled twice, but imagine this map wrapped around a globe and you will notice that the Ross Sea is connected into one large MPA (Data from protectedplanet.net).

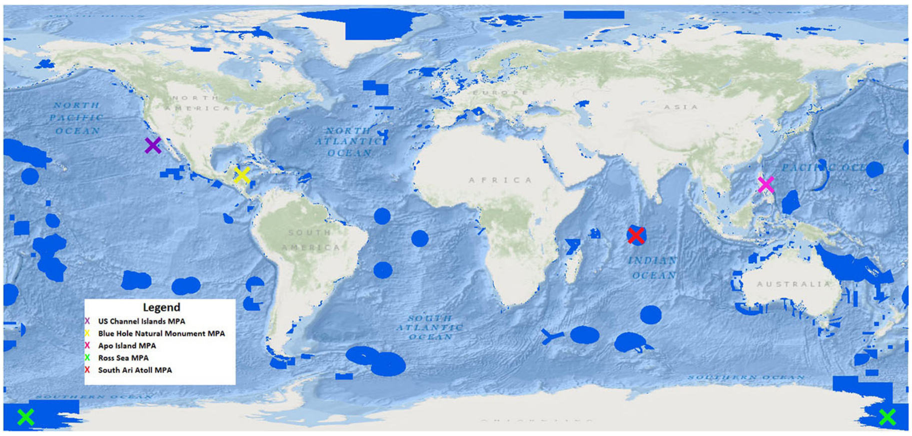

Figure 1

Because the categories of MPAs have such clear goals, the work of creating an MPA is made a bit easier. It is important the process of creating an MPA not be too difficult, because MPAs help to protect the marine environment, from the ocean floor to its surface, and they keep the ocean healthy for our future. The success of MPAs varies, but in general, an MPA is considered successful if its goals and objectives are reached [1].

WHAT MAKES A GOOD MARINE PROTECTED AREA?

Now that we know the goals of MPAs, we can now talk about what conditions make for a good MPA. Scientists have identified five qualities of MPAs that make them really good for protecting the ocean's biodiversity. The best MPAs have the following characteristics:

- **No-take zones**: As we explained above, a no-take zone means that human activity, such as fishing or boating, is strictly limited to ensure the protection of the marine environment.
- **Strong rules**: When an MPA has strong rules, it means that if someone does break the rules, there is a way for them to be punished, similar to the way breaking a classroom rule will land you in detention. Enforcement of the rules is difficult in the ocean. First, those enforcing the rules need to be on boats, which can be expensive to own, operate, and upkeep [1]. Second, MPAs, unlike protected areas on land, have many different access points. This means that those looking to break the rules have many ways to get into the MPA [1].
- **Old**: An "old" MPA means that it has been around for 10 or more years [2]. When an MPA is old, it has been around long enough to make a positive change, such as having more fish of a single type, more types of fish in the area, or bigger fish [2].
- **Large size**: When it comes to MPAs, bigger is better! A larger MPA means a larger part of the ocean is protected- that also means more ecosystem and species have that protection as well [2].
- **Isolated by deep waters and sand:** When an MPA is isolated by deep waters or by sand, it is easier to recognize the area as an MPA. Fishers will know that the space is protected, and therefore will know which rules go with that specific MPA [2].

When an MPA has these five features, the MPA generally shows double the amount of large fish species and five times more large fish **biomass** as compared to an unprotected part of the ocean [2]. This means that there are more, and bigger, fish. As of May 2020, just under 7.5% of the global ocean is protected through MPAs [4]. This may not seem like a lot, but just 20 years ago, <1% of the global ocean was protected [4].

BIOMASS

The total weight or volume of all organisms, in this case, fish.

WHO CAN MAKE MARINE PROTECTED AREAS?

So, can anyone create a marine protected area? Well, yes! A local community or a country's government can create MPAs [1]. Individuals who own beaches can create MPAs [1]. These types of MPAs would be closer to shore. But what about far away, in the **high seas**? 60% of the ocean falls in what is called the high seas, but <2% of the high seas are protected [3, 4]. Some parts of the high seas are governed by groups that are made up of multiple countries. For example, the

HIGH SEAS

Parts of the ocean that are 200 nautical miles (roughly 230 miles) from the shore of a coastal nation.

Figure 2

Figure 2

A map of the Ross Sea MPA. The boxes on the map show where the MPA will be, with the different abbreviations representing different categories of MPAs. The signatures of those who were at the CCAMLR meeting when it was adopted surround the map, including countries and non-governmental organizations (Credit to John B. Weller).

Southern Ocean that surrounds Antarctica is governed by a group called the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). This group is composed of 25 countries, along with the European Union. In 2012, two countries submitted an idea for a new MPA in the Southern Ocean [4]. It took until 2016 for the MPA to be allowed, because every country participating had to agree fully (Figure 2) [5]! Called the Ross Sea MPA (Figure 2), it is a category 1A MPA, because its main goal is to conserve the ecosystem and species of the Southern Ocean. It is also currently the largest MPA in the world [4]. What also makes the Ross Sea MPA special is that the Southern Ocean is one of the few really healthy parts of the ocean left, and it is home to important organisms like krill [5].

The Ross Sea MPA is seen as a marine conservation success story, because it is a very large, isolated, no-take MPA that has a lot of support from the countries that came together to create it [3–5]. The Ross Sea MPA is also part of a goal to create a network of MPAs that represent a wide range of marine habitats and environments, especially since so few MPAs exist in the high seas to date [4]. So, not only does the Ross Sea MPA meet four of the five aspects of a good MPA and is unique in its environment, but it also shows that countries can come together and cooperate to conserve parts of the ocean [3, 4].

WHY SHOULD WE CARE ABOUT MPAS?

Marine protected areas are a way for people to come together to preserve our oceans. There are many different types of MPAs, which allows governments or community groups to come together to choose the MPA that is right for their people. For an MPA to be the most effective at protecting fish and ecosystems, the MPA should be no-take, have strong rules, be around for a long time, be large in size, and be isolated.

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YOUNG REVIEWER

LUANA, AGE: 15

I like to roller skating, ride a bike, watch movies, and hang out with my friends.

AUTHORS

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CASSANDRA BROOKS

Cassandra Brooks is an Assistant Professor in Environmental Studies at the University of Colorado Boulder. She completed her Ph.D. at Stanford University studying international ocean policy, with a focus on marine protection in the Antarctic. During her previous graduate work at Moss Landing Marine Labs, she studied Antarctic toothfish in the Ross Sea, a population that supports the most remote fishery on Earth. Cassandra has worked in the lab, underwater, and at sea—including five research cruises to Antarctica—and has presented and published her work around the world. Cassandra is also trained as a Science Communicator through the University of California Santa Cruz and has published more than 150 articles and multi-media stories about marine science and the environment. Cassandra is also science faculty for the Homeward Bound Project, a ground-breaking women's leadership initiative in Antarctica.

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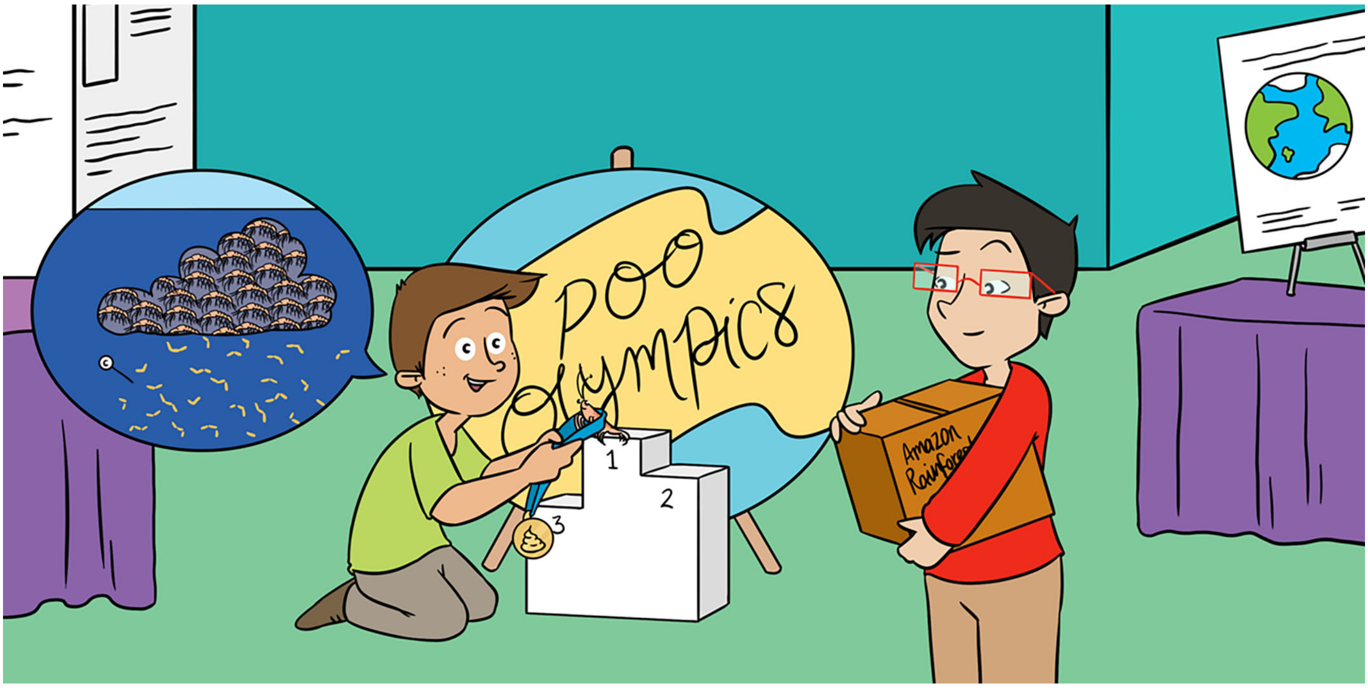

WHY KRILL SWARMS ARE IMPORTANT TO THE GLOBAL CLIMATE

***Anna Belcher*[1*], *Emma L. Cavan*[2] and *Geraint A. Tarling*[1]**

[1] *Ecosystems Team, British Antarctic Survey, Cambridge, United Kingdom*

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YOUNG REVIEWERS:

ST. MARY'S HIGH SCHOOL

AGE: 14

Ocean life helps keep atmospheric levels of carbon dioxide lower by taking carbon out of the atmosphere and transporting it to the deep ocean, through sinking particles. Antarctic krill live in the Southern Ocean and gather in huge swarms. Importantly, they produce large, fast-sinking poo (called fecal strings), meaning that we get a rain of poo below these swarms, which takes carbon quickly to the deep ocean. We calculate how krill lower the amount of carbon in the atmosphere by estimating how many krill there are and how many fecal strings each produces. These calculations reveal that Antarctic krill living near sea ice remove 39 million tons of carbon from the surface ocean each year. That is about the same weight as 100 million polar bears! Krill are therefore not only important food for whales and penguins, but also vital engineers of our climate and so they require protection.

A BIOLOGICAL SPONGE FOR CARBON

PHYTOPLANKTON

Microscopic plant-like algae.

ZOOPLANKTON

Animals that only have weak swimming movements so drift with the ocean/wind driven currents.

FECAL STRING

The type of poo produced by animals like Antarctic krill, containing lots of partly digested food inside a tubular membrane, often rich in carbon.

Our oceans are not only a fantastic playground where we can enjoy swimming and all sorts of fun activities, but they also play an important role in our climate. Full of amazing life, the tiny plants (**phytoplankton**) of the ocean are to thank for the oxygen in every other breath we take! In fact, without ocean life, levels of carbon dioxide would be about 50% higher than they are today [1]. Just like trees on land, phytoplankton in the ocean take up carbon dioxide and use sunlight to make the food they need to survive. In doing this, carbon gets locked up in the plant cells, which in turn are fed upon by marine animals, such as **zooplankton** and krill. Like all animals on land, marine animals do not use all the food they eat, and what they do not use, they pass out again as poo! Their poos (called **fecal strings**) are like tiny torpedoes packed with carbon, and as they sink through the ocean they take that carbon with them, locking it away from the atmosphere. Great news for reducing the carbon dioxide in our atmosphere!

Unfortunately, there are a whole bunch of animals living in the deep ocean looking for tasty snacks that rain down from above. The fecal strings from the krill, as well as dead marine plant and animal remains, sink through the ocean and most get gobbled up by the animals along the way. This means that only about 1% of sinking particles makes it all the way to the seabed. Once at the seabed, the carbon in these particles can be buried and locked away for millions of years in sediments and rocks. The more carbon we can get to the sediments, the less is in the atmosphere, which is great for our climate! The faster a particle sinks, the less time there is for it to end up on the dinner plate of a deep-ocean animal, so the more of its carbon reaches the seabed. It turns out that not all animals are created equal when it comes to the sinking speed of their poo!

KRILL POO: THE OLYMPIC SINKING CHAMPIONS

ANTARCTIC KRILL

Swimming crustaceans that live in the waters that
surround Antarctica.

Antarctic krill are swimming crustaceans (part of the same family of animals as crabs, lobsters, and prawns) that can grow up to about 7 cm in length and can live for up to 5–6 years in the wild (Figure 1A). They are only found in the Southern Ocean, the large expanse of ocean surrounding Antarctica. Krill are powerful swimmers and can swim against some of the strongest ocean flows in the world. In fact, krill never stop swimming their whole lives. This takes an incredible amount of energy, which they have to fuel by eating up to 10% of their body weight daily. That would be equivalent to us eating 12 full meals per day. However, rather than burgers and chips, krill food is mainly plant-based, particularly a type of phytoplankton called diatoms, which are full of energy and nutritional fats.

All that eating produces a lot of poo. One of the amazing things about krill is that their poo is produced in long chains called fecal

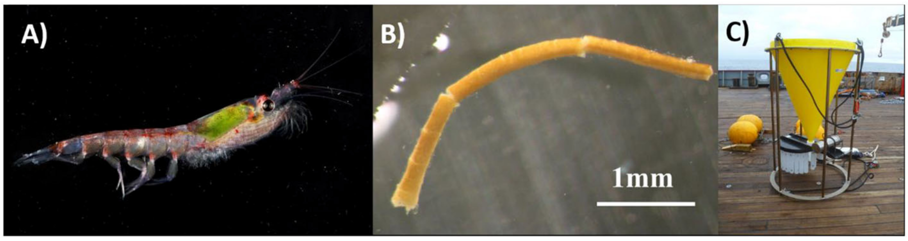

Figure 1

Figure 1

(A) An Antarctic krill (total length from eye to tail, 60 mm). **(B)** The sinking champion: krill poo. Krill fecal strings are compact, and their streamline shape means they can sink quickly through the ocean. They often form these long chains as shown. **(C)** One of the traps used to catch sinking poo.

strings (Figure 1B), which can sink quickly through the ocean at rates of hundreds of meters a day. Not quite Olympic sprinting speed, but they would win a medal in any poo-sinking race. In some parts of the Southern Ocean, we find lots of krill fecal strings in the collection traps that we leave out in the ocean. We deploy these traps on a long line that is usually anchored to the sea bed. The trap is essentially a big funnel that catches all the particles that are sinking down and collects them in sample cups at the bottom (Figure 1C). Sometimes the samples can be full of krill fecal strings and not much else, which we think is because there has been many millions of krill in the area swimming above the trap, in a large group called a swarm.

KRILL SWARMS: BIG IS BEAUTIFUL

One of the fascinating things about krill, which makes them even better at transferring carbon to the deep ocean, is that they hang out with millions of their friends in swarms. Some of these swarms are huge and can extend over areas of about 100 km^2 [2], which is about the same size as the island of Jersey off the UK. Krill much prefer being in a swarm than swimming separately, and it seems the bigger the swarm, the better. About 90% of all krill that live in the Southern Ocean hang out in a relatively small number of big swarms [3]. Being in a swarm offers protection from the many krill-eating predators, such as penguins, seals, and whales. It is also a better way to find the big patches (**blooms**) of their phytoplankton food that are scattered far and wide in the ocean; many pairs of eyes (and antennae) are better than one. These rare but huge swarms are really important, not only for the Southern Ocean wildlife that feed on them, but also for transferring carbon to the deep ocean, as lots of krill means lots of sinking poo!

BLOOM

A region of the ocean where there is a high concentration of marine plants caused by rapid reproduction.

THE KRILL CARBON HIGHWAY

Large krill swarms swim through the oceans, feeding on any blooms of phytoplankton that cross their paths. The sheer number of krill in these swarms means that, during this feeding frenzy, we get huge numbers of fecal strings that rain down below the swarm The huge number of fecal strings means that there is no way the poo-eating animals (such

Figure 2

The krill poo carbon highway.

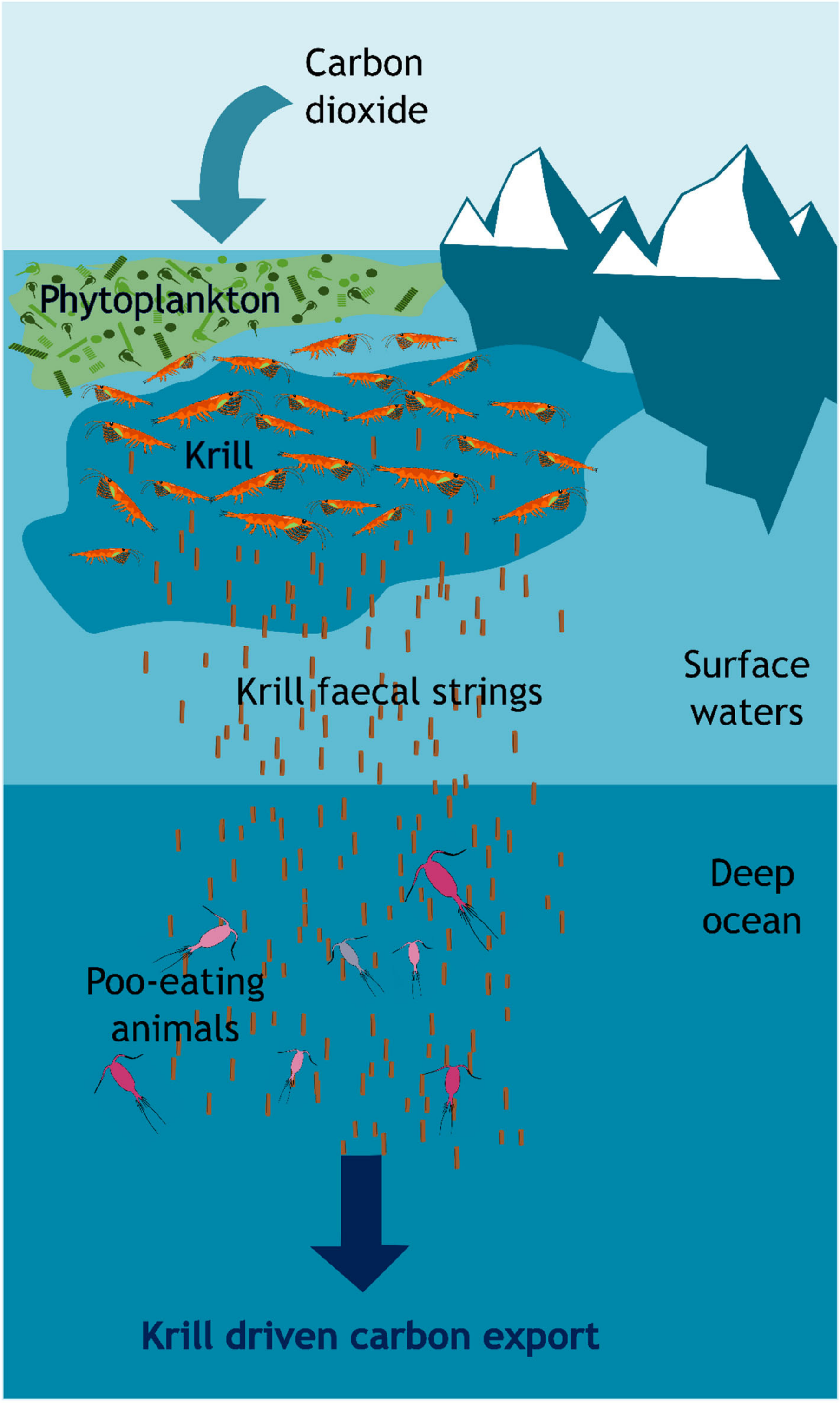

Figure 2

as fish and zooplankton) below can keep up with the supply—it is like being at a sushi bar and trying to eat huge platefuls of food as they come along at many times the normal speed! As these poo-eaters are overwhelmed, most of the fecal strings avoid being eaten and sink into the deep ocean, taking their carbon with them (Figure 2).

Lots of carbon can make it to the deep ocean when swarms of krill feed on phytoplankton near the surface, producing huge numbers of rapidly sinking fecal strings. There can be so many fecal strings that they cannot all be captured by the poo-eating animals living deeper in the ocean. This means lots of them can make it to the deep ocean, taking with them lots of carbon.

As these krill swarms are so few and far between, it is really difficult to capture these rare rain events, but we think they could transfer a lot of carbon to the deep ocean [4]. We wanted to find a way to estimate how many fecal strings are produced so that we could predict how much carbon they transfer out of the surface ocean. We particularly zoned in on a region of the Southern Ocean called the **marginal ice zone (MIZ)** The MIZ is where sea-ice starts to open up into the open ocean. We focused on the MIZ because conditions there are perfect for the generation of fast-sinking poo, since there are both lots of phytoplankton blooms and large numbers of krill. The location of the MIZ varies over seasons as the ice extent grows in the winter and melts back in the summer. As part of our calculation, we used satellite images to work out the size of the MIZ over the course of a typical year (Figure 3).

MARGINAL ICE ZONE (MIZ)

The transition zone between the pack-ice and the open sea, where there are varying amounts of ice and open water.

The next stage was to determine how many krill live in the MIZ. There have been many measurements of krill numbers in the Southern Ocean over the past decade, mainly using nets towed behind ships [5]. We put together all available records of net catches made in MIZ regions and estimated the numbers of krill in these regions over the course of a typical year.

The final part of the calculation was to work out how many fecal strings an average krill produces. We used information from a number of different science teams who fed captive krill and then measured the amount, size, and sinking speed of the fecal strings they produced [6].

Through putting these pieces of evidence together, we were able to estimate just how many fecal strings successfully make it out of the surface ocean and, more importantly, how much carbon they take with them. Our best estimate is that Antarctic krill living in the MIZ transport 39 million tons of carbon per year into the deep ocean through their poo. This is a minimum estimate, since many krill live in other areas beyond the MIZ. Nevertheless, this minimum estimate suggests that Antarctic krill transfer as much carbon in their poo as all of the carbon presently emitted from all the cars, buses, trains and even planes flying within the UK! Therefore, these social, hungry, phytoplankton eaters are also important climate engineers through doing what they must do every day—taking a poo.

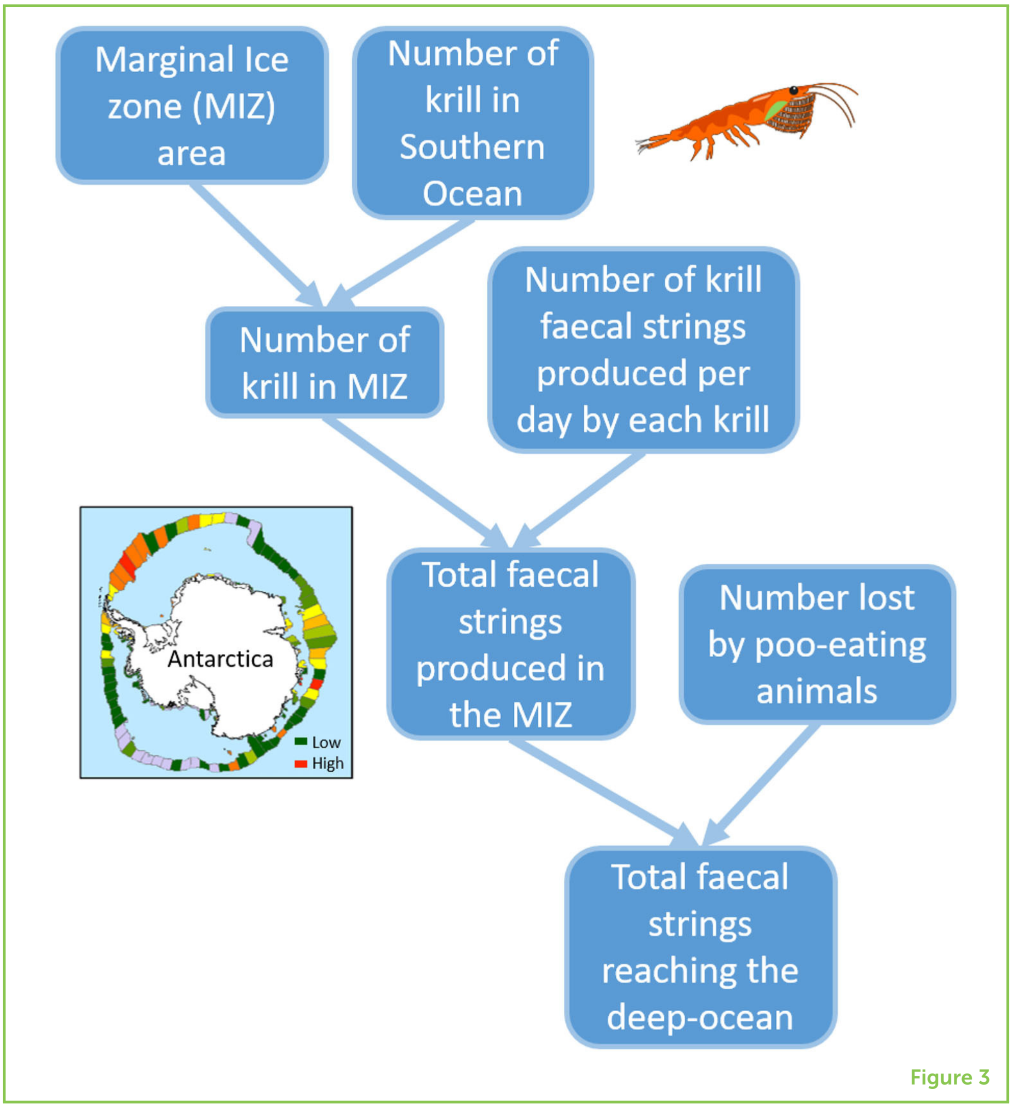

Figure 3

Steps in the model to estimate the number of krill fecal strings that make it successfully out of the surface ocean and take carbon to the deep sea. This keeps it out of the atmosphere! The map on the left shows where we find high (red) and low (green) numbers of krill in the marginal ice zone around Antarctica.

KRILL AND OUR CLIMATE

Once a poo, from krill or any other animal or fish, makes it to the deep ocean it will stay there for 10, 100, or even 1,000 years! This is really important for the climate, as it means carbon is locked in the deep ocean and cannot return to the atmosphere as carbon dioxide, which is what is causing the planet to warm so quickly. It can be hard to study animals in the ocean, and we are only just learning how important their poo is. So, we need to be careful about what we take from the ocean and the impact we have on ocean communities, not only because krill are important food for many animals, but also because their poo may be important for the climate! However, next time you are in a storm, be grateful that it is only water that is falling on your head!

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ORIGINAL SOURCE ARTICLE

Belcher, A., Henson, S. A., Manno, C., Hill, S. L., Atkinson, A., Thorpe, S. E., et al. 2019. Krill faecal pellets drive hidden pulses of particulate organic carbon in the marginal ice zone. *Nat. Commun.* 10:889. doi: 10.1038/s41467-019-08847-1

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YOUNG REVIEWERS

ST. MARY'S HIGH SCHOOL, AGE: 14

St. Mary's is a Catholic, college-preparatory school developing students in grades 6–12 from more than 30 communities on Boston's North Shore. Shaping authentic men and women of talent and faith. The Honors Biology course focuses on developing scientific inquiry skills that can be applied throughout the students' academic experiences. It has been an incredible experience for our students to get direct experience in the peer-review process and we are so excited to see the final product.

AUTHORS

ANNA BELCHER

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

EMMA L. CAVAN

I research how animals and plants living in the sea and rivers interact with the environment. I now work at Imperial College London, having worked at the University of Tasmania (Australia) for 2 years. My first research as a Ph.D. student was on the importance of plankton poo in the ocean carbon cycle and so I am often known as Dr. Plankton Poo! My main scientific interest is how climate change will impact our environment and the health of our oceans. In my spare time I enjoy finding any excuse to get to the UK coast, stopping my dog from chasing birds, relaxing on the sofa, and a good old-fashioned English pub!

GERAINT A. TARLING

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

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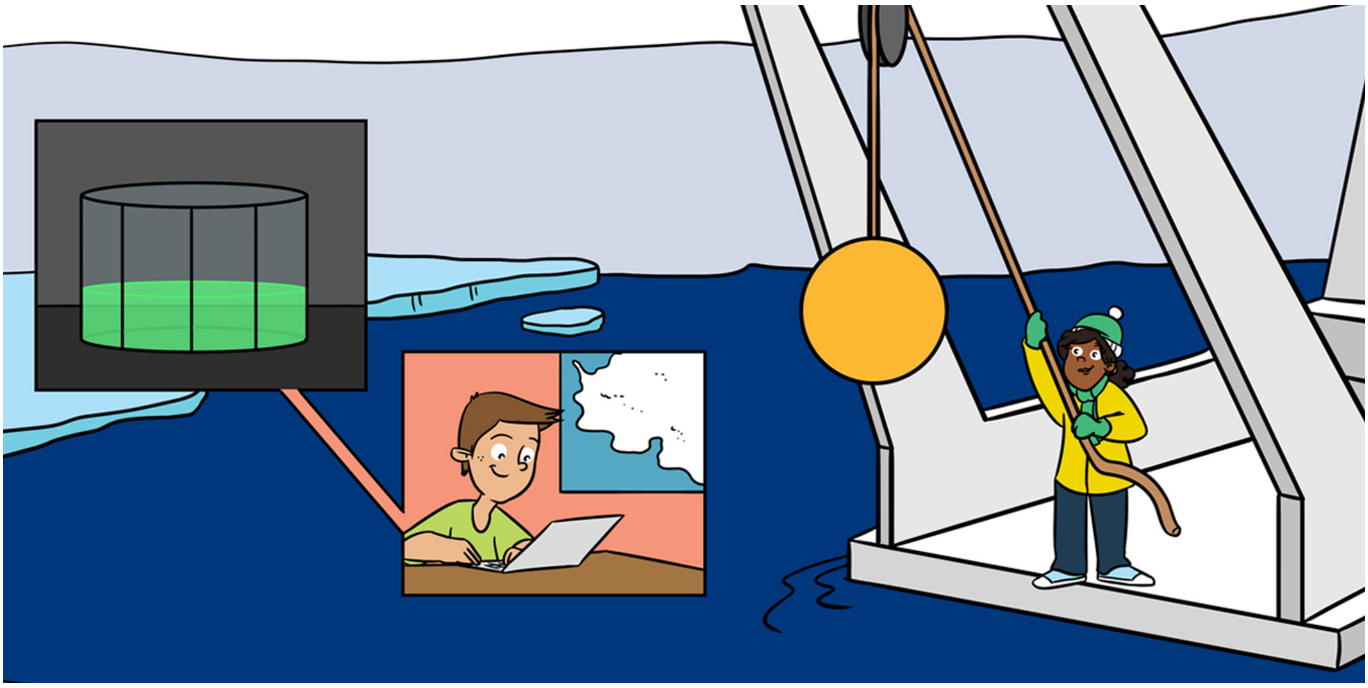

ARE WARM OCEAN CURRENTS MELTING THE ICE IN ANTARCTICA?

Mirjam S. Glessmer [1*]***, Nadine Steiger*** [2]***, Elin Darelius*** [2] ***and Anna Wåhlin*** [3]

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YOUNG REVIEWERS:

ISABEL
AGE: 9

MARGARIDA
AGE: 12

We went to Antarctica on a research ship to set out instruments, which stayed in the water and took measurements for 2 years. While the instruments were out, we went to a research facility and had a swimming pool full of water turn around on a big merry-go-round for 2 months. We did all this to understand whether warm currents are melting ice in Antarctica [1]. What was the answer? Let us start from the beginning…

VERY COLD AND VERY FAR AWAY: A FROZEN CONTINENT AND ITS IMPORTANCE

Antarctica—the huge landmass at the South Pole—is the only continent that nobody lives on permanently (Figures 1A–D). It is very cold—the average temperature is −10°C (14°F) near the coast and −60°C (−76°F) in the interior. Antarctica is almost completely covered in a sheet of snow and ice. This **ice sheet** is up to 5 km (3 miles) thick

ICE SHEET

Large ice masses that cover Greenland and Antarctica. They form as it snows and rains and more and more ice accumulates, and can be up to 5 km thick.

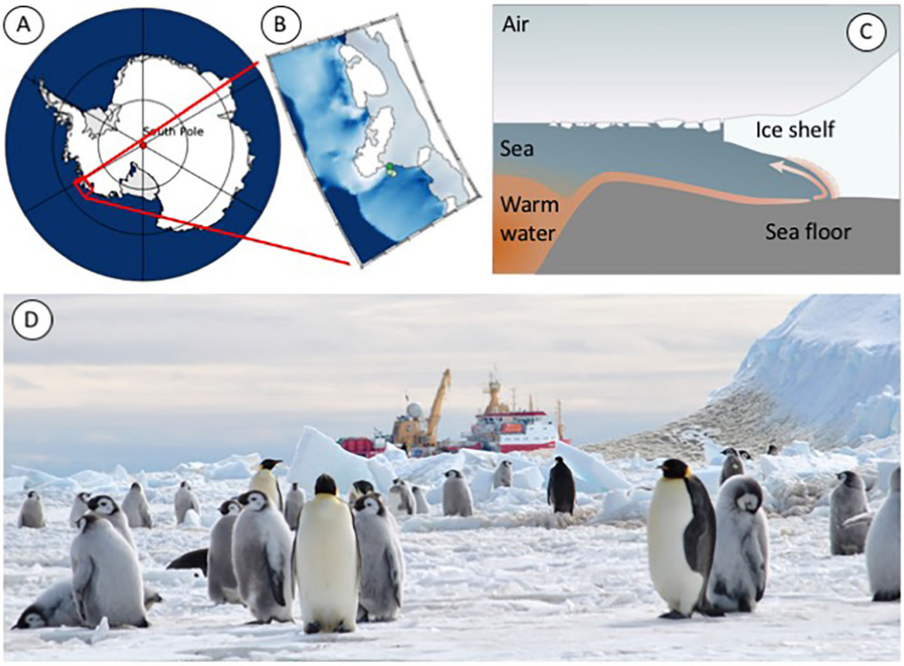

Figure 1

Figure 1

(A) A map of Antarctica and the region we are specifically interested in (red box). **(B)** The green dots mark the locations of our moorings. **(C)** This is what an ice shelf would look like if it were cut open and looked at from the side. Part of it rests on land and the sea floor. It is flowing toward the open ocean, and gradually thinning due to melting. Parts of the ice shelf break off and float away. A current of relatively warm water flows toward the ice shelf at the sea floor. **(D)** The research ship RV Shackleton on one of its journeys to Antarctica, laying moored near an ice shelf.

and grows thicker as snow falls on it. The parts of an ice sheet that float on the ocean but are still attached to the ice sheet are called **ice shelves**. They can extend for many kilometers away from the land. There, big ice bergs break off and leave a wall of ice that reaches 250–500 m (820–1,640 ft) down into the ocean.

It is important to distinguish ice shelves and ice bergs from **sea ice**, even though all three float on the ocean [2]. Sea ice forms when water in the ocean freezes, similar to ice that forms on lakes. When sea ice melts, it does not add extra water to the ocean, thus sea level does not change. Ice that originates on land, however, causes **sea-level rise** when it melts. The glaciers on Antarctica start out as an ice sheet resting on land, but their offshore parts float on the ocean. Those parts act as a stopper that keeps the rest of the ice on land. If the floating ice melts, more ice will slide from land into the ocean and cause sea-level rise.

The worst-case estimates predict that the sea level could rise 5 cm/year (2 in/year). This is really fast! Imagine a spot near the ocean where you get slightly wet toes right now. Forty years from now, the water level could already be above your head! It is important to be able to predict how fast sea level will rise so that we can prepare for it. Therefore, we need to understand how much ice is really melting and what causes melting.

ICE SHELVES

Large ice sheets that flow off land and float on the ocean, but are still connected to the ice that is still resting on land. They can be several hundreds of meters thick.

SEA ICE

Ice that forms when sea water freezes. It floats on the ocean (see https://kids.frontiersin.org/article/10.3389/frym.2019.00079).

SEA-LEVEL RISE

Long-term average rise of the ocean's water level. The melting of Antarctic and Greenland ice caps is contributing to sea-level rise.

THE OCEAN IS MELTING ANTARCTICA'S ICE

Ice has been melting faster over the last decades because of **climate change**, due to warmer air temperatures and because more ice is breaking off and floating away, but also because of the warmer water around Antarctica [3]. The world's strongest **ocean current** circles all around Antarctica. In some places it brings relatively warm water (1–2°C; 34–36°F) toward the ice shelves [4], warm enough to melt ice if water and ice contact each other. But do they?

CLIMATE CHANGE

The long-term change in climate patterns like temperatures, precipitation, ocean currents, and sea levels. Climate change occurs naturally and leads to warm and cold periods, but most recently it is caused by humans.

OCEAN CURRENT

The average motion of water in the ocean. Ocean currents can be driven by different processes, like the wind or density differences in the water (see my article https://kids.frontiersin.org/article/10.3389/frym.2019.00085).

Since the sea floor around Antarctica is full of narrow, deep valleys, those canyons could funnel the warm water toward the ice, similar to water slides that funnel you down into the swimming pool. If the currents manage to flow underneath the ice shelves, this could increase melting from below. The thinner the floating ice shelves become, the faster ice will slide off Antarctica.

But it is difficult for warm currents to get underneath the floating ice shelves. At their thinnest parts, they still reach 250–500 m deep into the water. Imagine the ocean as a room with the ocean surface as its ceiling: the ceiling would suddenly drop by 250–500 m where the ice shelves start. This change in height makes it more difficult for currents to flow underneath. In our imaginary room, people wanting to go underneath the dropped ceiling might have to duck or even crawl, which some might be better at than others. Similarly, there are different kinds of currents—those that stay close to the ground and dive below an obstacle, and those that cannot. But which sort of currents do we have around Antarctica, and does the warm water actually get close enough to the ice to melt it? There are several ways to find out.

FIGURING OUT HOW FAST THE ICE IS MELTING, AND WHY

It seems like we could easily take a research ship, sail to Antarctica, and observe the currents directly. But there are several reasons why this is not easy. The weather there is bad and the ocean is covered in sea ice during winter, threatening ships, and crews. Therefore, data taken from research ships only exists in selected locations for short periods of time, and only in summer.

MOORING

Oceanographic instruments that are anchored to the sea floor and stay in the ocean for a certain time period to collect data. Moorings can measure ocean currents and the temperature and salinity of sea water.

An alternative are instruments that stay in the ocean for long periods of time (Figure 2). **Moorings** are anchored to a fixed location on the ocean floor, thus giving measurements in that location specifically. Floats are drifting with the currents and therefore provide data only where the currents take them. Instruments can also be mounted on seals, giving data wherever the seals choose to swim. Gliders are like small submarines and move slowly, remotely controlled through the water, but need a research ship nearby. And, even for instruments, it is dangerous to be too close to the ice edge—there is a lot of both

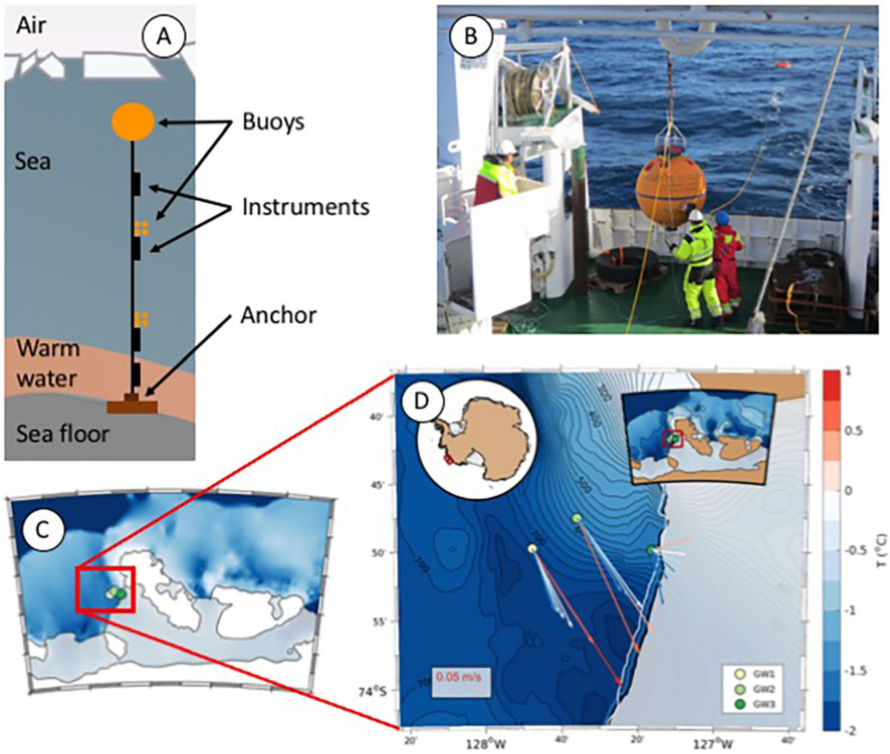

Figure 2

Figure 2

(A) A mooring in the ocean, showing the anchor that keeps it in place, the buoys that keep it upright, and the various instruments to measure the water's temperature, how much salt there is in the water, and the direction and speed of the currents. **(B)** A mooring being deployed over the stern of a research ship. The large orange ball hanging on the crane is a buoy that carries instruments that will measure currents and that keeps the mooring upright in the water. Behind the research ship, you can see other parts of the mooring already floating in the water. **(C)** A map of our mooring sites (same as Figure 1B, only rotated). **(D)** The results from our three moorings: arrows show the direction that the currents are flowing, colors show the temperatures of those currents.

skill and luck involved in deploying and recovering instruments! It stays exciting until the very end: will we find the instruments again, get them back on board, and will they actually have recorded for the full period of time they were in the ocean? The data can only be read from the instruments when they are safely back on board the ship.

A second approach to understanding the warm currents and ice shelves is to simulate the system by building it in miniature (imagine a model railway). Then, we can change the shapes of the ice shelves or the canyons in our model, for example, to understand the impact of each change on the current's behavior in the real world.

MEASURING DIRECTLY IN THE OCEAN

We set out moorings with instruments that can tell us about water temperature and the direction and strength of ocean currents at three sites over a period of 2 years: one right at the front of the ice shelf and two along a canyon that funnels water towards the ice shelf. Data from two moorings showed water flowing toward the ice shelf. The third mooring, closest to the ice shelf, showed the current turning just before reaching the ice shelf. That means the current's warm water does not continue straight underneath the ice shelf. Instead, it turns and flows along the front of the ice shelf before flowing back into the

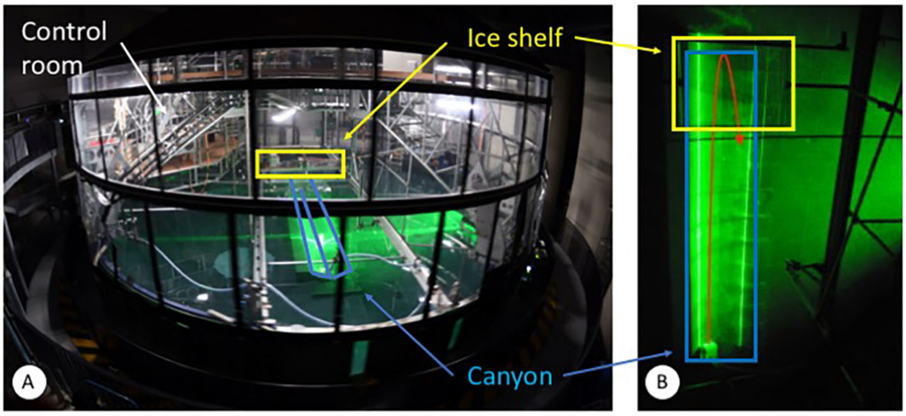

Figure 3

Figure 3

(A) An outside view of the 13 m diameter rotating swimming pool. Note the control room that rotates with the pool, as well as the "ice shelf" and "canyon" in the water. **(B)** A top view of the model canyon (blue) underneath the ice shelf (yellow). The current (red) is flowing underneath the ice shelf, then turns and flows out again.

open ocean. Therefore, the ice is not melting as much as it would if the current went underneath the ice shelf.

RECREATING OCEAN CURRENTS IN A MINIATURE WORLD

In the lab in Grenoble, France, we found the explanation for why the current turns around (Figure 3). We used a 13 m diameter pool that rotates, simulating Earth's rotation. We built a plastic canyon to represent our area of interest in Antarctica. We then pumped water into the canyon to create a current. The end of the canyon was covered by a plastic "ice shelf" that we could rise, lower, and tilt to create different conditions. We made the currents visible by mixing little plastic particles into the water and lighting them with lasers. Following where particles moved between photographs of the laser-lit particles, we could reconstruct the currents.

For an ice shelf that starts with a steep step, the current nibbles at the ice edge, but it is forced to turn around without flowing underneath the ice. With only very little water movement underneath the ice, there is little melting there. However, if the shape of the ice sheet is changed so that it starts at the sea surface and then gradually reaches deeper into the water, it is easier for currents to move under the ice. An ice shelf of that shape will melt faster. Also, if the structure of the current changes such that only the lower part is moving, it might behave differently, and more water might be able to get under the ice shelf.

COMPUTER MODEL

A way to represent physical processes on a computer that allows scientists to understand an environment, or predict the effect of future changes. Weather forecasts are an example. For a good explanation see https://kids.frontiersin.org/article/10.3389/frym.2019.00161.

PREDICTING THE FUTURE

Now that we know how the shape of the ice shelves as well as the type of currents approaching them influence how fast ice melts, we can use that to help predict future sea levels. **Computer models**, similar to those used for weather forecasts, can accurately calculate where the ocean currents go and how much ice they melt. This information then becomes one piece in the puzzle of climate predictions that can help make policy decisions to both prevent and adapt to changing sea levels.

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ORIGINAL SOURCE ARTICLE

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YOUNG REVIEWERS

ISABEL, AGE: 9

Hi, I am Isabel and I am from Portugal. I am 9 and I like reading, writing, and music. I have three cats and I like to learn about history. I have no idea of what I want to be when I grow up. I really like vegetables (and fruit).

MARGARIDA, AGE: 12

My name is Margarida, I am 12 years old and I like reading, climbing, and writing. I love science, especially anything about black holes, and I have absolutely no idea what I want to do when I grow up. I also really like biology.

AUTHORS

MIRJAM S. GLESSMER

Dr. Mirjam S. Glessmer is a physical oceanographer. She is fascinated by water in all its forms: she loves to go "wave watching" on puddles, streams, or the sea, or to do experiments on ocean physics using only household items ("kitchen oceanography"). Mirjam is passionate about sharing her fascination with all things related to ocean physics and you are welcome to contact her if you have questions, at www.mirjamglessmer.com/contact or *mglessmer@gmail.com

NADINE STEIGER

Nadine Steiger is a Ph.D. student in physical oceanography and is learning a lot about the ocean. She loves the magic of the polar regions with all the beautiful ice—how does it connect with the ocean and the rest of the climate system? So far, she is already had the chance to go on a research cruise to Antarctica and she worked for 2 months on the rotating platform in France, mesmerized by the green light that visualizes the currents in the water.

ELIN DARELIUS

Dr. Elin Darelius is a polar researcher and a physical oceanographer working at the University of Bergen. She loves ice and cold water (but not for swimming) and she has been on four research cruises to Antarctica. She helped deploy the moorings that were used in this study, and she went swimming in the rotating pool in France (where the ice shelf was plastic and the water was nice and warm). You are welcome to visit her blog (https://skolelab.uib.no/blogg/darelius/) to read more about what she does.

ANNA WÅHLIN

Professor Anna Wåhlin is a physical oceanographer. She is fascinated by water and ice, and how water and ice interact in the polar seas on Earth. To understand the ocean, she goes on research cruises to collect data, but she also works with laboratory experiments and computer models. She enjoys teaching students about the physics of the oceans at her university, which is situated in Gothenburg, a small city on the West coast of Sweden.

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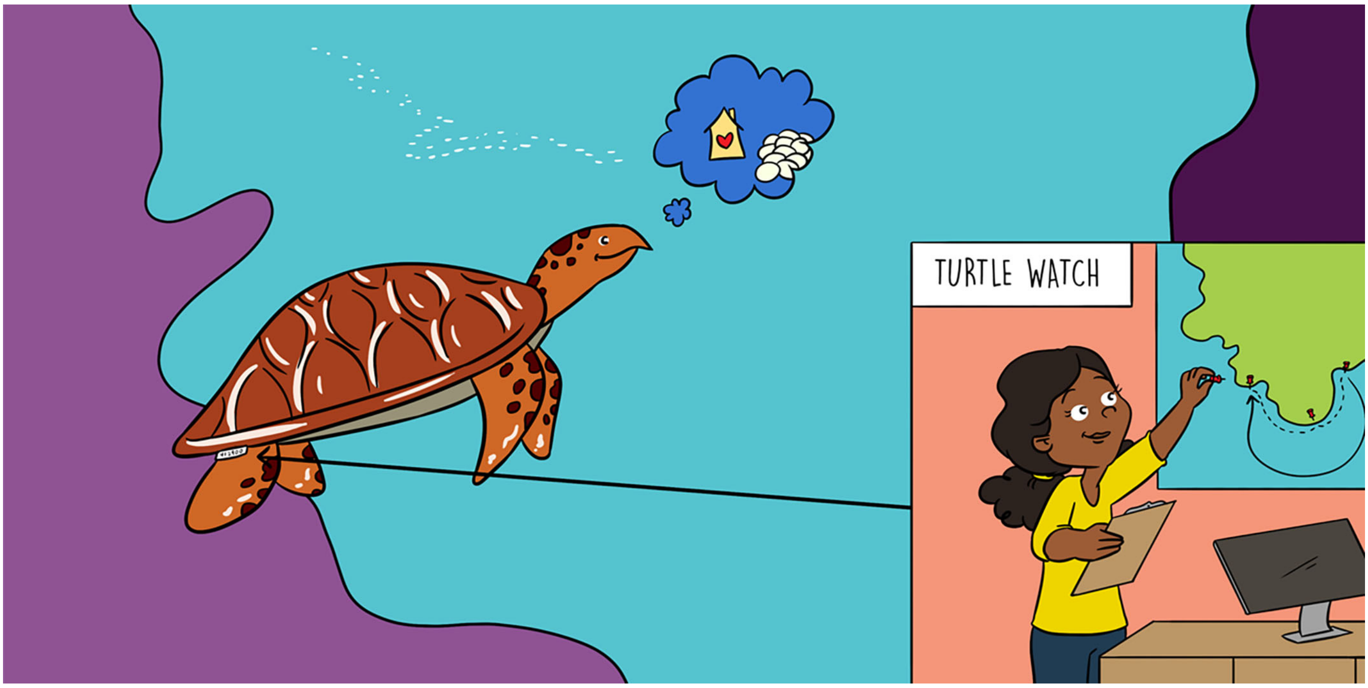

FOLLOWING THE JOURNEY OF SEA TURTLES ON THEIR QUEST FOR FOOD

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YOUNG REVIEWERS:


CAILLIN
AGE: 13


LILU
AGE: 11


MAIA
AGE: 10

Why is it important to know where turtles look for food? Sadly, many sea turtle species are classified as endangered. Scientists are working very hard to understand where the turtles eat and live. At different stages in a turtle's life, it requires different types of food that can come from ocean currents, protected bays, or open coastal areas. Knowing which areas the turtles prefer at which stages of their lives will help us locate them and lead to a better way of protecting all turtles, young and old. We have explored new feeding grounds along the North Pacific coast of Costa Rica. This work will help the conservation of these precious animals.

WHAT IS THE LIFE CYCLE OF A TURTLE?

A hawksbill turtle hatches from her nest on a moonlit beach, to the soft sound of waves calling. In a neighbouring nest, a male baby green

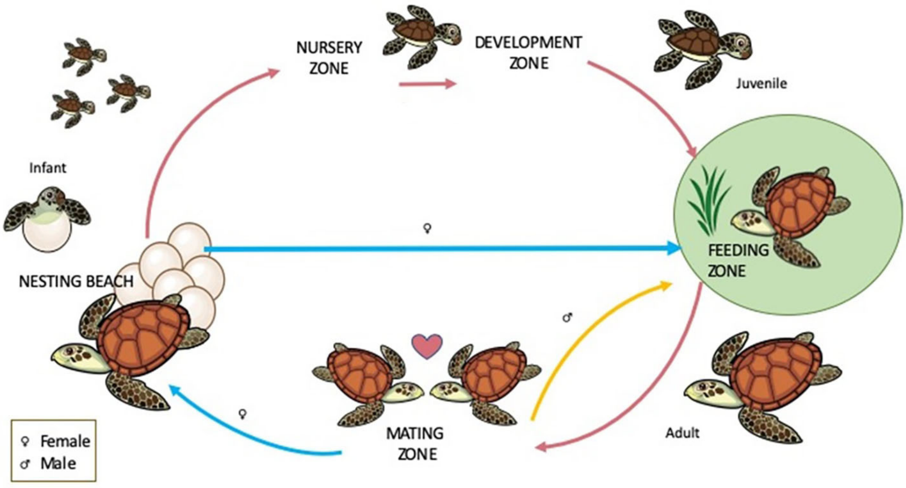

Figure 1

Figure 1

The life cycle of a sea turtle, from hatching to ocean life. Different zones, or areas of the ocean, are often used during the various life stages. Females return to the same beach they were born on to lay their eggs.

turtle is also born. As they scurry to the ocean, a raccoon and a dog are watching from the bushes. The turtles must be quick to avoid these predators! Luckily, they know where they are going; the moon's reflection on the ocean is pointing them in the right direction. Once they have crossed the crashing waves and escaped the hungry fish, they have made it to the strong marine current, where they drift for many years using branches as a natural net to catch the food they need. No one really knows where the baby turtles go or what they do during these "**lost years**."

After those "lost years," the turtles become teenagers (**juveniles**) and are so hungry that they need to find a **foraging** ground. This is a safe and protected place where food is plentiful and diverse; hawksbills sure do like to eat sponges and small organisms that are hiding in the coral. Green turtles will preferably look for seagrass and seaweed [1]. When the turtles become adults and want to start families, they might have to move to a larger and richer foraging ground if the one they live in becomes insufficient. As they get older and stronger, turtles can face the challenges of an unprotected bay.

Both species of turtles will look for a reproductive site where they can meet their partners. At this point the female has started her reproductive migration and set off to the beach where she hatched, to lay her own eggs (Figure 1). The male, however, will go straight back to the foraging grounds and the female will join him later. Now that we know the turtles will spend a lot of time at the **feeding grounds**, we will use the work of scientists to help us understand more about the lifecycle of turtles and how to protect them!

HOW DOES A TURTLE CHOOSE ITS FEEDING GROUND?

Most of the study sites are rocky, have coral, and are affected by the tide and waves. In some parts, there are also mangrove swamps and

LOST YEARS

No one knows exactly what baby turtles do and where they go in the first few years of their lives as they follow the marine currents. This is why scientists refer to that period as the "lost years."

JUVENILE

A turtle that has not reached adulthood. This can take up to 45 years for some species.

FORAGING

Looking for food.

FEEDING GROUND

Area where the turtles eat. Also called foraging ground.

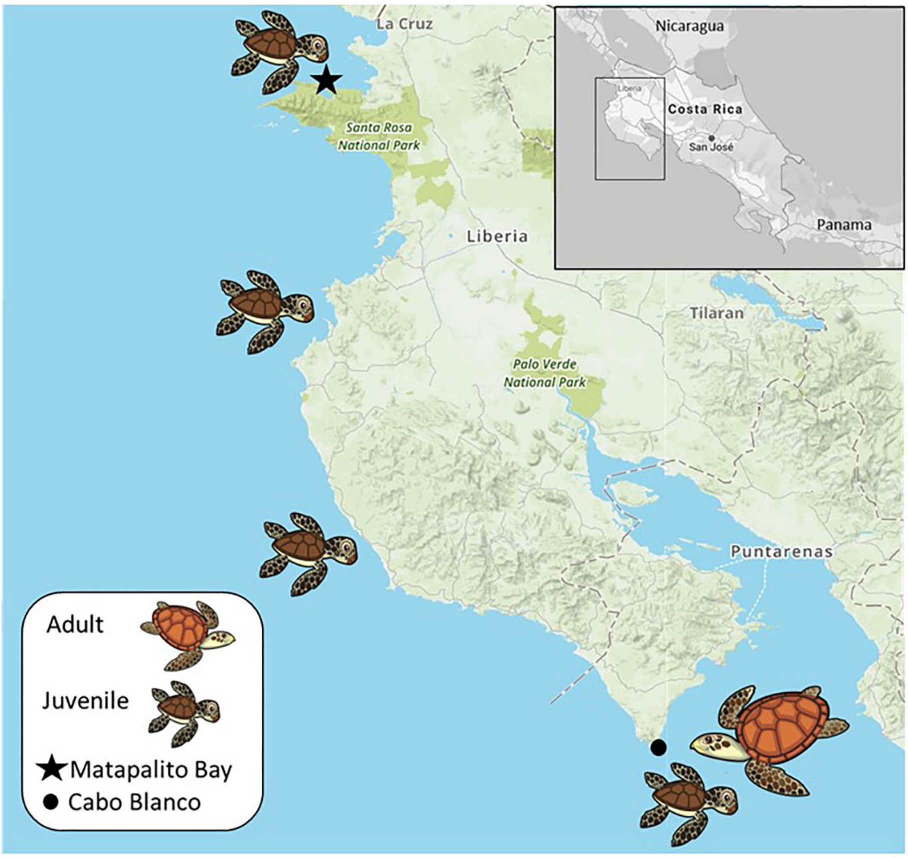

Figure 2

Figure 2

Feeding ground preferences of juvenile/adult hawksbill and green turtles in Guanacaste, Costa Rica. Juveniles are found more in areas like the protected bay of Matapalito. Adults are found in more open areas like in the bay of Cabo Blanco, alongside some juveniles still.

long blades of seagrass. Depending on the kind of site, we spot more turtles either in the dry season or the rainy season. This is probably due to the type of food in the sea or the arrival of food from the land, thanks to the rain. The Matapalito Bay (Bahia Matapalito) is a good example of a feeding ground where researchers are studying the turtle populations all year round (Figure 2). The bay has a sandy bottom and a coral reef, so it provides diverse feeding options. The turtles rest underneath coral formations along the edge of the reef, by the sandy stretch. Research shows that the hawksbill turtles seen at this site are mostly juvenile. This suggests that the area might be an important developmental ground for young turtles. As well as the abundance of food, the turtles probably like this bay for the many places to hide in the reef and rocks, which provide protection from larger predators. A bay, such as Matapalito also provides shelter from the rough, open sea where waves and currents can be very strong.

In Matapalito, we recaptured a small juvenile green turtle with the same characteristics as turtles in the Western Pacific. This suggests that the site is really important for juveniles, no matter where in the world they come from. This could be because there is a lot of food available and good protection provided by the bay. On other, less protected sites, for example Cabo Blanco (Figure 2), which are probably richer in food sources, we see more adults than juveniles.

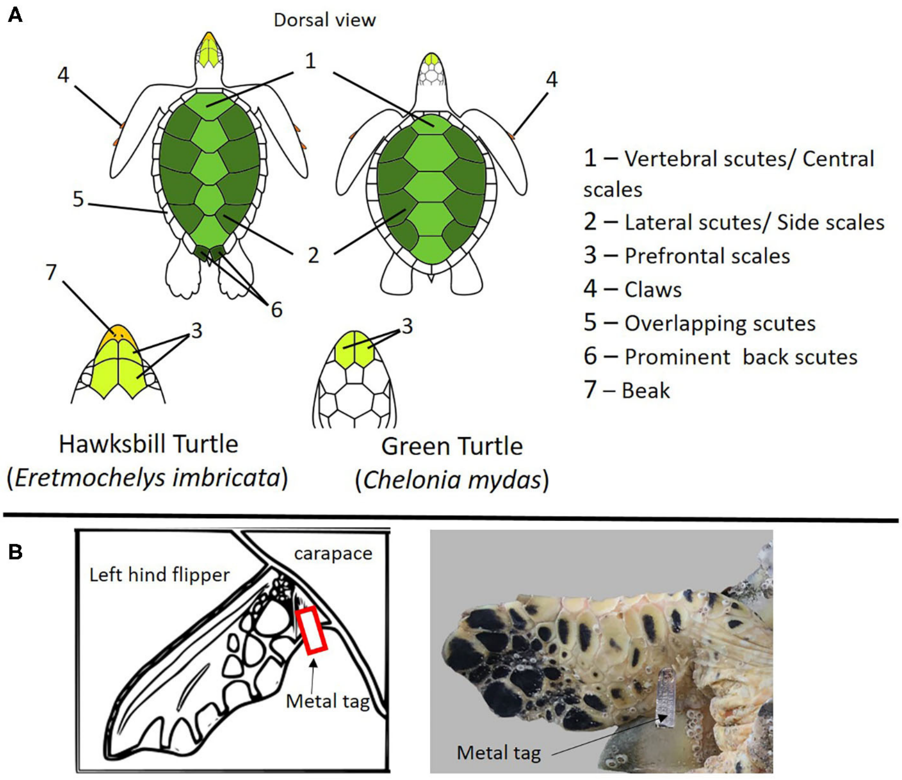

Figure 3

(A) A comparison of the physical appearance of hawksbill and green turtles. The physical differences allow us to tell the two species apart. **(B)** Tagging zone on the turtle's back flipper. Carapace is the technical term for the shell. Scutes are external bony plates on a turtle's shell.

HOW DO WE IDENTIFY TURTLES?

We can identify a turtle's species by looking at its physical characteristics. For example, the hawksbill turtle has a pointy beak similar to a parrot and black skin with a yellow pattern on its face. The shell is sharp on the side. The green turtle, on the other hand, has green-grey skin, with a different symmetrical pattern on its face, a round head, and an oval shell (Figure 3). We identify male turtles by their long pointy tails that only grow when they have reached adulthood. This can take up to 30 years for some species!

To carry out research on turtles, we catch them by casting out a special turtle net from the boat. The net is 80 meters long and 6 meters deep, with holes 45 centimetres wide, to stop the nets from catching small fish. The turtles are brought onto the boat where they are measured, weighed, and tagged. Scientists capture and tag turtles to follow their migrations. The tag is a unique, numbered, flat piece of metal that is clipped to the turtle like an earring (Figure 3). The turtle will carry this identification number for the rest of its life. Nowadays, some scientists tag turtles on the back flipper, which has been found to be the best place [2]. When the tag is on the front flipper, the turtle is more at risk of getting caught in a fisherman's net when trying to catch an easy dinner! Once tagged, scientists around the world will be able to note where the turtle was previously captured, and therefore where it has been. Tagging turtles provides a lot of information on their behavior. For example, scientists have followed a green turtle that travelled all the way from Mexico to Costa Rica and back. Tagging also allows us to follow turtles that stay in the same feeding grounds for years. This is how scientists have found that some turtles are loyal to their foraging grounds—through tagging and recapture!

WHAT ARE THE THREATS TO THE TURTLES?

Most turtle species are endangered and need our immediate help to survive. There are several reasons why most sea turtles are endangered, and many of them are because of humans. For example, building hotels and houses by the beach disrupts the life cycle of turtles. Turtles like their peace and quiet; mothers will not lay eggs on busy beaches. Unnatural light is also a problem, especially for baby turtles who will confuse it with the moonlight and end up going away from the sea instead of into it.

Two highly significant reasons for the decline of all sea turtle populations are egg poaching and hunting. For example, hawksbills, which are considered critically endangered because their populations are dropping so quickly, are frequently hunted because they are the only turtles with scales on their shells, and those scales are used to make jewellery. Since they live near the coast, hawksbills are also the first species to be hunted for meat.

Additional threats to the turtles are fishing lines, hooks, and nets, which can cause turtles to get tangled or hurt, and the large quantity of plastic in the ocean, such as water bottles, shopping bags, and straws, which turtles may eat by accident, causing them to choke or have serious stomach problems [3]. These problems affect green turtles for example and that is why they are classified as endangered.

Last, global warming affects the entire life cycle of the turtle. Scientists in Brazil have shown that warmer temperatures and more sun led to fewer baby hawksbill turtles being born [4]. Increasing ocean water temperatures could also affect the sources of food the turtles might need.

HOW CAN WE HELP?

In conclusion, this article described the life cycle of two species of turtles found on the Pacific coast of Costa Rica: the green turtle and the hawksbill turtle. Furthermore, the threats faced by turtles and the importance of helping turtles by gathering data on their locations and eating habits has been explained. Scientists are working hard to understand every stage in the sea turtle's life cycle by collecting and sharing data. This is the only way to connect research with conservation. Some conservation strategies are already in place, for example, people around the world are taking action by patrolling the beaches to protect the eggs from poachers and predators. You can also do something to help. Everyone can! Telling your friends and family what you know about turtles and the struggles they face will help raise awareness and can promote habitat preservation. Not using objects like balloons, bottles, bags, or straws can also really help reduce the growing amounts of plastic in the ocean and save the turtles!

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ORIGINAL SOURCE ARTICLE

Heidemeyer, M., Arauz-Vargas, R., and Lopéz-Agüero, E. 2015. New foraging grounds for hawksbill (*Eretmochelys imbricata*) and green turtles (*Chelonia mydas*) along the northern Pacific coast of Costa Rica, Central America. *Rev. Biol. Trop.* 62:109–18. doi: 10.15517/rbt.v62i4.20037

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YOUNG REVIEWERS

CAILLIN, AGE: 13
Hi, my name is Caillin and I live in the Highlands of Scotland. I like to dive and snorkel and play with my pet cat, Noah. I am flameshell ambassador for the Ullapool Sea Savers, a group of kids who (like me) want to help save our beautiful seas. Flame Shells are little shellfish that live in the sea—they are really cool and have bright orange tenticles and they build reefs.

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

MAIA, AGE: 10
Hello my name is Maia—I am 10 years old, I live in highlands of Scotland. I love to read and play with my pet dog Polly and my cat Tatty, I also have two sisters Caillin and Kira they are very nice and kind. I am the white tailed sea eagle ambassador for the Ulapool Sea Savers, a kids marine conservation group. We work to protect our Marine Protected Area and have fun.

AUTHORS

AOIFE TAYLOR
I have a degree in chemistry and am currently doing a Ph.D. at the University of Manchester, investigating how plants make chlorophyll. My love for animals and interest in learning about conservation brought me to Costa Rica. I was amazed by

the diversity of the wildlife and particularly interested in exploring marine life. During my placement with ETC I was given the opportunity to get involved in a locally run project to protect sea turtles, it was an incredible experience!

EMILIE GERARD

I am a French/British Ph.D. student at the University of Manchester looking at quick and less energy costly way to make drugs using enzymes. I got my chemistry master's degree from the University of Sheffield in 2018. During my 3 months placement in Costa Rica at ETC, I saw many cool, diverse animals, and a lot of turtles! It was a great experience being a part of an organization that helps protect these beautiful animals. *emilie.gerard@manchetser.ac.uk

HANNAH HAARMANN

I was born in Germany, but most of my childhood was spent in Namibia which meant going on safaris and playing outside whenever I could. In 2015, my family and I moved to Switzerland where I finished school. For my gap year I volunteered for 3 months in Costa Rica with Equipo Tora Carey and 1 month in Malawi working with the Lilongwe Wildlife Centre. Soon, I will be starting my studies in wildlife conservation and see where life takes me from there.

MATHILDE GIRY

I am originally from France and have lived in Costa Rica since 2009, where I and my husband raise my son Noa amidst nature. I am the Environmental Educator for a local NGO, ETC, where I assist in marine life research. I also translate scientific data into accessible language, especially for kids from coastal communities. My values for conservation are extended into my everyday practices. As a professional kite surfer and captain, I promote nature-based sports and eco responsible behavior.

MAIKE HEIDEMEYER

I am originally from Germany and graduated from the University of Costa Rica with a Master's in biology, where I am currently working as a researcher. I have been researching sea turtles for over 10 years and am the co-founder of the NGO "Equipo Tora Carey."

† These authors have contributed equally to this work

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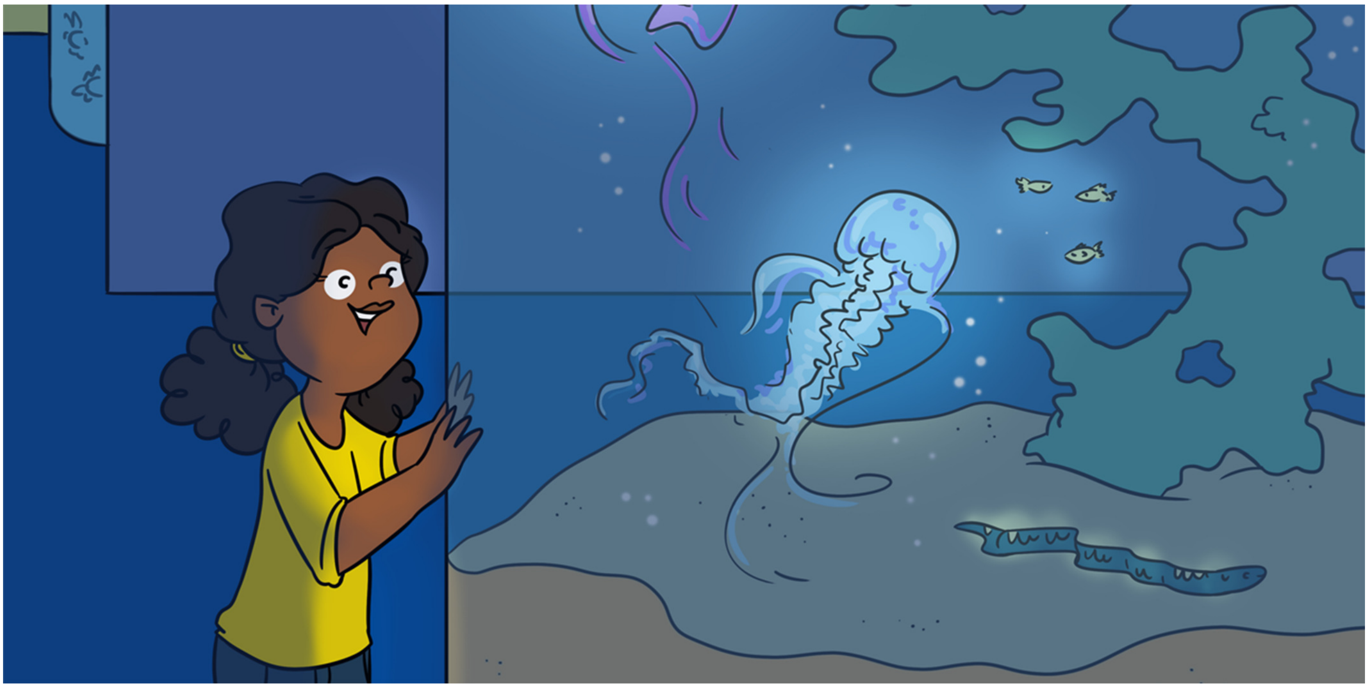

THE DARK OCEAN IS FULL OF LIGHTS

***Séverine Martini*[1*] *and Warren R. Francis*[2]**

[1] *UMR7093 Laboratoire d'Océanographie de Villefranche, Villefranche-sur-Mer, France*

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YOUNG REVIEWERS:

JOHN FISKE ELEMENTARY SCHOOL

AGES: 12-14

Imagine that your body could emit light whenever you needed it. You would never be afraid in the dark or at night, because you could light up the world around you. You could shoot a flashing cloud under your bed so that monsters in the darkness would be blinded, while you escape. Many animals in the ocean can actually do that; this superpower is called bioluminescence! In the open sea, about three quarters of all animals are bioluminescent, and these animals can live anywhere from the surface down to 4,000 meters deep. This light emission is an efficient way to communicate with mates, attract prey, or escape predators in the darkness of the oceans.

INTRODUCTION

BIOLUMINESCENCE

The emission of light by living organisms.

Do you know that most marine animals have a superpower that we do not have? It is called **bioluminescence**, from the words "bios," meaning life in Greek, and "lumen," meaning light in Latin. Bioluminescence is the ability of some living organisms to emit their own light. The word bioluminescence may sound similar to other

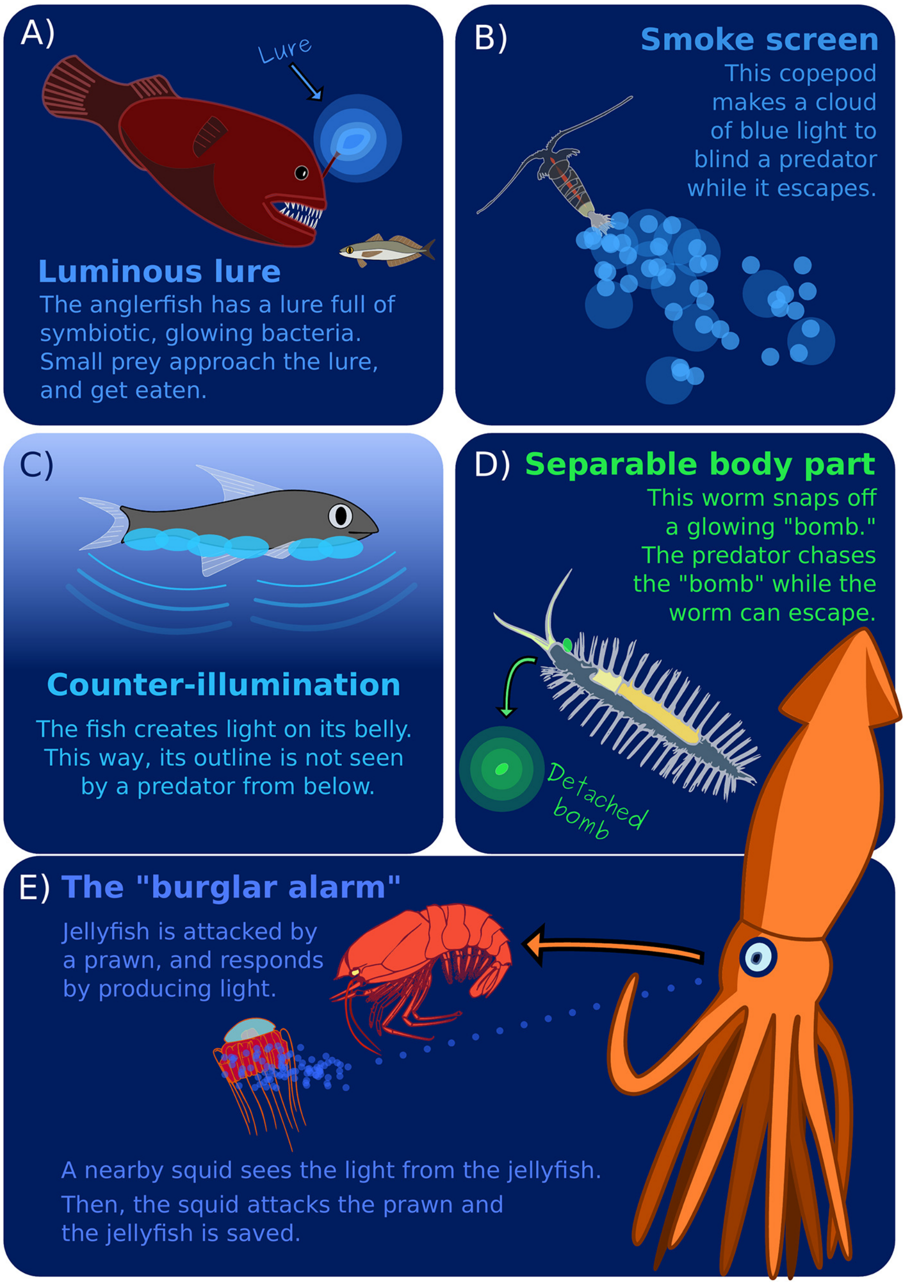

Figure 1

Various ways that deep-sea animals use bioluminescence. **(A)** Luminous lure, **(B)** smoke screen, **(C)** counter-illumination, **(D)** separable body part, **(E)** "burglar alarm".

words, like "phosphorescence" (think of glow-in-the-dark toys), or "fluorescence" (think of highlighter markers), but they are completely different phenomena [1]. The main difference is that bioluminescence does not require any source of external light, like the sun or a flashlight. Bioluminescence is actually a chemical reaction (more like a glow-stick). This reaction was described for the first time in 1887 by the French biologist Raphael Dubois. The bioluminescent reaction requires two chemicals, one called a **luciferin** (which gets used up like batteries) and the other called a **luciferase** enzyme. The two chemicals react together, with a bit of oxygen, to produce light.

LUCIFERIN

A chemical acting with the luciferase during the bioluminescence chemical reaction.

LUCIFERASE

An enzyme involved into the bioluminescence chemical reaction.

WHY EMIT LIGHT?

Why do animals put their energy into making light? One reason to emit light is that, in the ocean, the sunlight barely penetrates deeper than a few hundred meters. Below that, it is completely dark. During the night, even the ocean surface is dark, except for the faint glow from the moonlight, so light is a great way for animals to communicate. But who are they communicating with and who else is seeing these signals? For marine species, emitting light or looking for light in the darkness helps them to find partners or even something to eat. For example, the angler fish uses its glowing lure to attract small prey that will undoubtedly end up in its stomach (Figure 1A). Of course, since the prey do not want to be eaten, they can use bioluminescence too, but as a defense. Many different strategies can be used [2]. Shooting a cloud of luminescent mucus is a way to leave predators dazzled for a few seconds (Figure 1B). Indeed, imagine that you have been in a dark room for a few minutes. If someone comes in and points a flashlight at your eyes, you will be blinded for a few seconds and unable to see anything—just enough time for the potential prey to escape.

Some fish and squid use bioluminescence for counter-illumination (Figure 1C). Normally, if these animals swim at the surface during the day, their silhouette against the sun would be visible to predators swimming beneath them. However, some fish and squid can produce light from their bellies to disrupt the silhouette and hide them from would-be predators. Another strategy used by some squid and worms is to detach part of their body as a sacrificed luminous target (Figure 1D). A predator then chases the glowing detached part while the prey escapes, similar to the way some reptiles can detach their own tails to escape predators. Lastly, some animals use light to attract help if they are being chased, which is sometimes called their "burglar alarm" (Figure 1E). Animals that are slow or fragile can have trouble escaping a predator by themselves, so they use the light to call out to something bigger and meaner that might want to eat the organism harassing the fragile animal.

DIVERSITY OF LUMINOUS MARINE ORGANISMS

Bioluminescent organisms are uncommon on land, though perhaps you have seen bioluminescent fireflies in your garden or in the countryside. In the ocean, however, they are found everywhere. There is a wide diversity of luminescent animals: fish, squid, jellyfish, some corals, different kinds of marine worms, ctenophores (pronounced "TEEN-o-fours," comb-jellies), sea stars, and crustaceans (some shrimps, for example). Among even stranger luminous animals, pyrosomes are organisms that look like long, gelatinous tubes (Figure 2A). They emit unusual brilliant, sustained light and, more amazingly, they luminesce in response to external light stimulation (Figure 2B).

Figure 2

Figure 2

Pyrosomes: interesting bioluminescent animals. Pyrosomes are free-floating tube-shaped animals. They can range from a few centimeters to few meters in length. **(A)** A pyrosome observed under white light, which is like the light from the sun, or a lightbulb (©MBARI). **(B)** A pyrosome glowing, using bioluminescence (with permission from S.H.D. Haddock, ©biolum.eemb.ucsb.edu/).

Most of the bioluminescence emitted by ocean animals looks blue or green, which are the colors (or wavelengths, in physics) that travel the furthest underwater. It has been observed that green light emitters are mainly found in shallow environments, while blue-turquoise light emitters are more often **pelagic** creatures, meaning they live in the open water [3]. However, the entire rainbow is used by bioluminescent organisms. Some jellyfish make light that looks purple. The marine worm named *Tomopteris* (pronounced "toe-MOP-ter-iss") emits yellow light in the form of bright glowing particles, a very uncommon color to emit in the deep sea. Scientists still do not understand how or why *Tomopteris* produces yellow light. Lastly, some fish, called dragonfish, even make red light. At this extreme wavelength, our eyes can barely see the red light, but our cameras can. The red light is probably used to search for prey, since most of the dragonfish's prey cannot see red light either.

PELAGIC

Relating to the open water of the ocean, as distinguished from the benthic regions of the ocean.

The light emitted from bioluminescent animals is usually very short-lived, lasting from <1 s to about 12 s. The patterns of light are very diverse. Short flashes of bright light are emitted by copepods, and clouds of bioluminescence are produced from some ctenophores, siphonophores (relatives of jellyfish that form long chains), or chaetognaths (commonly called arrow worms). Another example is the sea cucumber, which does not look very pretty under normal light. However, in the dark, when some of them luminesce, we can see amazing, circular patterns of light over their entire bodies, like living fireworks[1]. The most incredible thing is that there are certainly many more bioluminescent patterns hidden in the deep ocean that nobody has ever seen.

[1] https://www.nature.com/articles/d41586-018-06660-2

Figure 3

Bioluminescent animals can be found throughout the ocean. Pelagic organisms are found in the water column, and around 76% of these animals are luminous. Benthic organisms are found close to the seafloor, and 30–40% of them are luminous.

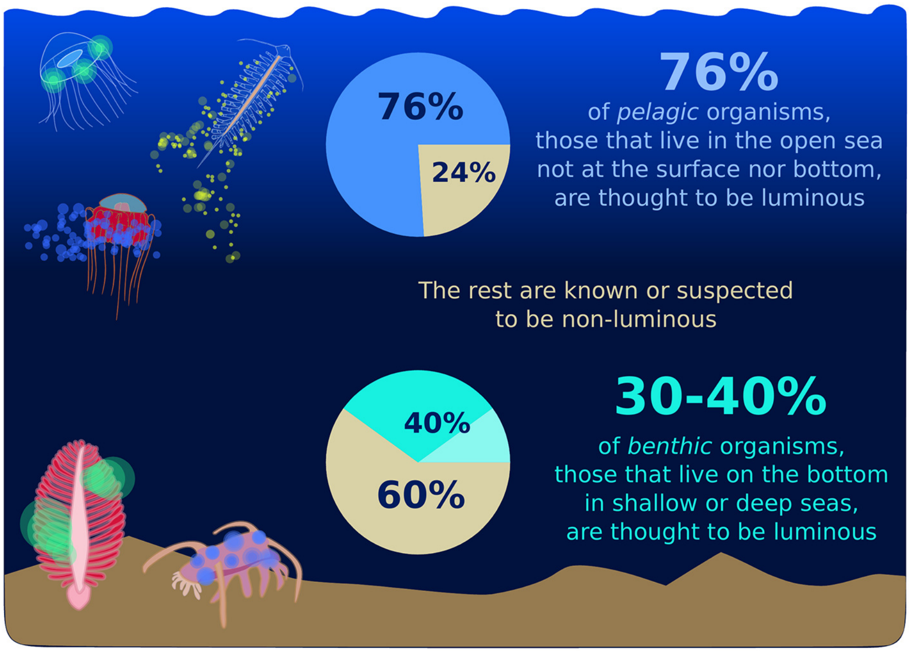

Figure 3

It is not just larger ocean animals that use light in these ways—some microscopic organisms can also be bioluminescent. Dinoflagellates (pronounced "dino-FLA-jel-lits") are often responsible for the bioluminescence observed at the sea surface. Their luminous traces can sometimes be seen at night behind sailing boats or if you disturb the water with your hand, at the beach. Even bacteria can be bioluminescent. Contrary to larger organisms, the light of bioluminescent bacteria is continuous. Bioluminescent bacteria can be found everywhere in the ocean: free in the water, attached to substances like plankton poop, or carcasses, or even in fish guts. These bacteria can also be found in a symbiotic relationship with other animals, living in specific light-organs of certain fish or squid. Like a team, in which each member of the team contributes something helpful, the larger animal provides nutrients (food) to the bacteria and, in return, uses the bacterial light to attract prey. A common example is the angler fish. This fish, which lives very deep down in the ocean, has a luminescent lure filled with luminous bacteria on its head, acting like a fishing rod. The anglerfish and bacteria are living together in a symbiotic relationship. However, bioluminescence through **symbiosis** is not common, and most organisms are self-luminescent, using specialized cells called **photophores**.

SYMBIOSIS

Interaction or close living relationship between organisms from different species, usually with benefits to one or both organisms.

PHOTOPHORE

Light-emitting organ present in some bioluminescent animals.

HOW COMMON IS BIOLUMINESCENCE IN THE OCEAN?

Researchers in submarines have reported that, during their descent into the deep ocean, a lot of the creatures disturbed by the vehicle were sparkling. However, it remains very difficult to observe these

BENTHIC

Relating to the bottom of the sea or to the organisms that live there.

glowing animals in their environments, several thousands of meters below the ocean surface. Recent analysis estimates that 76% of pelagic organisms (those that live in the open water) have the ability to emit light [4]. This means that most of the animals living between the surface and the deep ocean have this super-power. For **benthic** organisms (those that live close to the seafloor), the percentage is a little bit less—about 40% of these animals are bioluminescent (Figure 3). Such variability is linked to the wavelengths of light that are most visible in these environments. Why is there such a different percentage of luminous pelagic animals compared with benthic animals? One main hypothesis is that bioluminescence is a way to communicate. To communicate with someone far away, light is very effective in the pelagic environment. On the contrary, for benthic animals, there are a lot of obstacles like rocks, cracks, and caves, or the water can be cloudy due to sediment stirred up by ocean currents. As a result, using light is probably not as effective for benthic organisms. Light might also be less necessary for bottom-dwellers, since there are many places to hide.

CONCLUSION

Bioluminescence is a fascinating superpower possessed by many of the marine creatures living in our oceans and frequently shown in movies or TV shows. While scientists have been aware of this ability and its mechanism for centuries, we are still far from understanding everything about bioluminescence. Indeed, researchers have not discovered all the reasons why animals or bacteria are bioluminescent. Also, the chemical reaction that creates bioluminescence, while understood for some animals, still remains secret for many other animals, such as some worms and many fish.

It is important for scientists to keep studying bioluminescence, because this fascinating ability of organisms remains undescribed or barely understood in many animals, while it has a major importance in the dark ocean.

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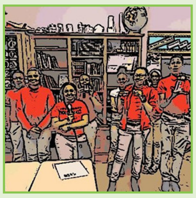
YOUNG REVIEWERS



JOHN FISKE ELEMENTARY SCHOOL, AGES: 12–14

We are group of students at smart young scientists participating in SMART science club. We are interested in different chemicals and substances. We are in seventh and eighth grade at John Fiske Elementary School. We are excited about the opportunity to work with scientists who study and write about bioluminescence. Our names are Joi, Brianna, Kingsley, Taliya, Hallel, Shamari, Shamar, and Camron.

AUTHORS

SÉVERINE MARTINI

I started working on bioluminescent bacteria during my Ph.D. in Marseille, France, at the Mediterranean Institute of Oceanography. My goal was to understand how these microorganisms adapt to the deep sea (high pressure and darkness). To pursue my research on larger marine species (jellies, invertebrates…), I worked for 2 years at the Monterey Bay Aquarium Research Institute (MBARI), in California, USA. MBARI is a world-leading laboratory specialized in deep-sea research and technologies. *martini.severine@gmail.com

WARREN R. FRANCIS

My background is in biochemistry. I did my Ph.D. in California at the Monterey Bay Aquarium Research Institute, studying bioluminescence in a group of animals called ctenophores, the comb jellies. I have ongoing projects on a variety of luminous animals, polychaetes, squid, corals, and jellyfish, from both genetic and chemical perspectives.

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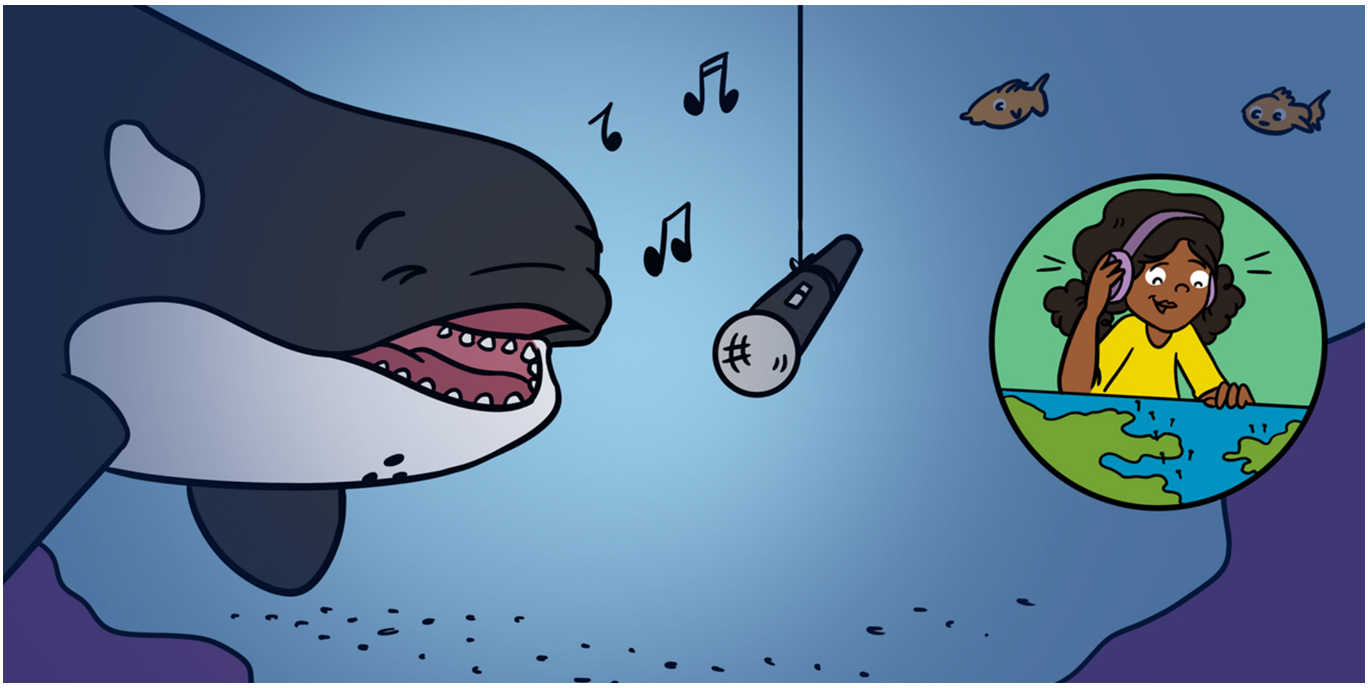

LEARNING ABOUT WHALES BY LISTENING FOR THEIR CALLS

Rianna Burnham *

Geography Department, The Whale Research Lab, University of Victoria, Victoria, BC, Canada

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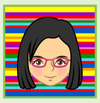

JUNIPER
AGE: 10

Populations of large whales have been reduced to very low numbers, primarily by hunting. As the number of whales became smaller, they became harder to find. In the past, whalers knew where to go to hunt, but now scientists who study whales can find it hard to know which areas whales use to feed, breed, or even travel through. We now realize how important whales are for keeping oceans healthy, so scientists are trying to learn as much as they can about large whales. Underwater sound recordings are helping us find some of the rarest whales in the northeast Pacific by listening for their calls. We use underwater microphones, called hydrophones, set on the ocean floor and on ocean gliders, which are small submarines, to help us learn about where whales are, when they are there, and most importantly, what they are doing.

WHALES HUNTED ALMOST TO EXTINCTION

Whales were once hunted for oil, meat, and many other things that people used in everyday life. Whalers killed many whales, decreasing whale populations until many large whale species almost became extinct. Despite the end of hunting over—30 years ago, some of these species still only survive in small numbers. Some species are so rare that scientists do not know how many whales there are in the population, where they live, how they move through the oceans, or if they have special areas to feed, breed, and raise their calves. Some whales, like gray and humpback whales, live closer to the land in shallower waters where the sea floor is a gentle, sandy slope away from the coast. This area is called the **continental shelf**. Whales living on the continental shelf have recovered from whaling and are fairly easy to study. But whales, such as blue whales and fin whales are large and live in deeper waters far from the coast, called offshore areas. At the end of the continental shelf is a steep drop that creates a cliff face under water, where the water becomes very deep very quickly. This is called the continental shelf break. It is here that the larger whales like to live, which makes it very hard for scientists to study them.

CONTINENTAL SHELF

The shallow areas of the ocean closest to land. The ocean floor is a gentle slope away from the coast, with water usually <200 m deep. The shelf comes to an end with a steep drop and a rapid increase in water depth, forming a cliff face known as the continental shelf break.

WHALES CAN BE HARD TO FIND!

The first thing we need to know to help save whales from extinction is how many of each type of whale there are, and where they are located. You might think it would be easy to count very large whales, but they can be hard to find in the deep offshore waters. Scientists also want to know where whales might get together to be social, feed, and breed, as these actions are very important for whales' survival. Scientists also want to know other things, like whether the whales have enough food, and whether people are changing the oceans in ways that make it harder for whales to live.

Sometimes scientists cannot look for the whales in person—it might be hard, dangerous, or just too far. Instead, we use underwater microphones, called **hydrophones**, to listen for them. We will describe how hydrophones were used to listen for whale calls in the Canadian Pacific Ocean, off the coast of Vancouver Island. These hydrophones were located both on the ocean floor and on ocean **gliders**, which are small submarines. One of the hydrophones on the ocean floor was fairly close to land and the other was at the bottom of the steep continental shelf break. The glider can be controlled from land, and we moved it between these two hydrophones to survey for whales, listening for their calls (Figure 1). The hydrophones on the sea floor recorded all the time, but the glider could only record for a month before its batteries needed replacing. We used the gliders to survey twice, once in the spring (Figure 1, red line) and once in the winter (Figure 1, blue line). We listened on the continental shelf in shallow water, past the continental shelf in deep water, and in cracks in the cliff face of the continental shelf break, called **canyons**. Sometimes the small animals that whales eat get trapped in these canyon cracks because of the way the water moves inside them, and so we thought whales might be there to feed.

HYDROPHONE

An underwater microphone used to make recordings of the sounds of the ocean.

GLIDER

A survey tool that can be controlled by scientists. The glider looks a bit like a submarine and can move around the ocean using batteries for power, going up and down in the water as it moves.

CANYON

A crack in the cliff face formed by the continental shelf break.

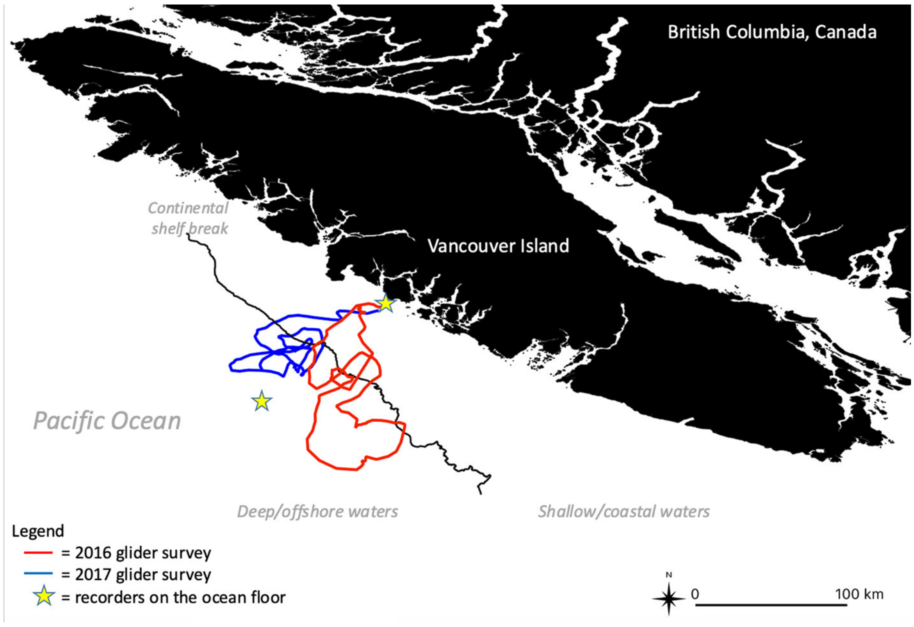

Figure 1

Figure 1

Location of hydrophones (stars) on the ocean floor and glider survey tracks from our experiments. The spring survey is shown in red and the winter shown in blue. The continental shelf break (black line) is shown to indicate where shallow coastal waters change to deep, offshore waters.

PITCH

How high or low a sound is. For example, when a dog whines, it is a high pitch, when it growls, it is a low pitch.

We were hoping to hear blue, fin, sei, and sperm whale calls. Each whale species makes a specific sound, which means we know which whales we are hearing. These calls can be high or low in **pitch**, long or short, they can go up-and-down or be flat in pitch, or they can sound like a whistle, a moan, or a click (Figure 2). The larger whales, like blue and fin, make long, low, moans that go down in pitch. Smaller whales and dolphins, such as killer whales make short, higher-pitched whistles, and humpback whales make moans and whistles that change in pitch. Sperm whales and the other smaller toothed whales use clicks. Whales' calls can also help us learn what the whales are doing. Some calls are used more frequently when whales are traveling or mating, and other calls tell us that they are feeding.

LOCATING WHALES AND IDENTIFYING THEIR ACTIVITIES

In the spring, on the first glider survey (Figure 1, red line), we heard gray whales first, as they called to each other while traveling along the coast of North America to their feeding areas in the Arctic. As the glider got further away from shore, we heard humpback whales, then when the glider went into even deeper waters, we heard what was most likely the feeding calls of fin and blue whale calls (Figure 2; [1]). A few faint sei whale calls were also heard. Many sei whales were killed back when whales were hunted, and they have not been seen very much at all since the 1950s. From the hydrophones on the ocean floor, we heard smaller whale species closer to the coast and larger whales in waters past the continental shelf break (Figure 3). The deeper hydrophone on the ocean floor also heard lots of sperm whale and dolphin clicks.

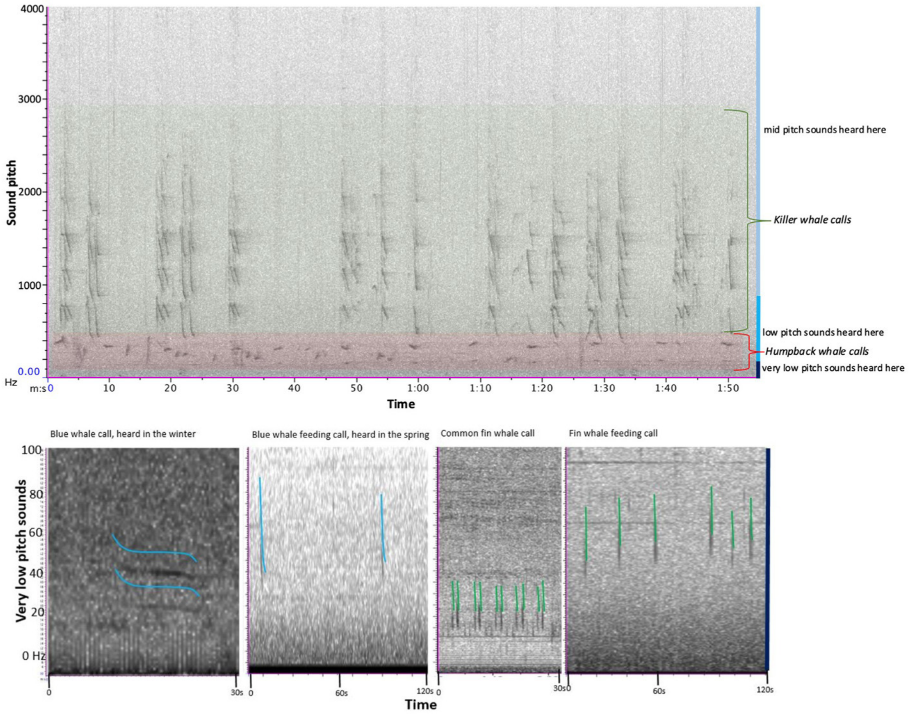

Figure 2

Figure 2

Pictures of the sounds that the whales were heard making, showing the pitch range of the calls and how the pitch changed during the call. The top panel shows humpback and killer whale calls heard during the surveys. The humpback calls are in the lower pitches (at the bottom of the picture) and killer whale calls are higher in pitch, in the mid-range. In the lower panels, blue and fin whale calls are shown. These are very low calls, lower than those of both humpback and killer whales.

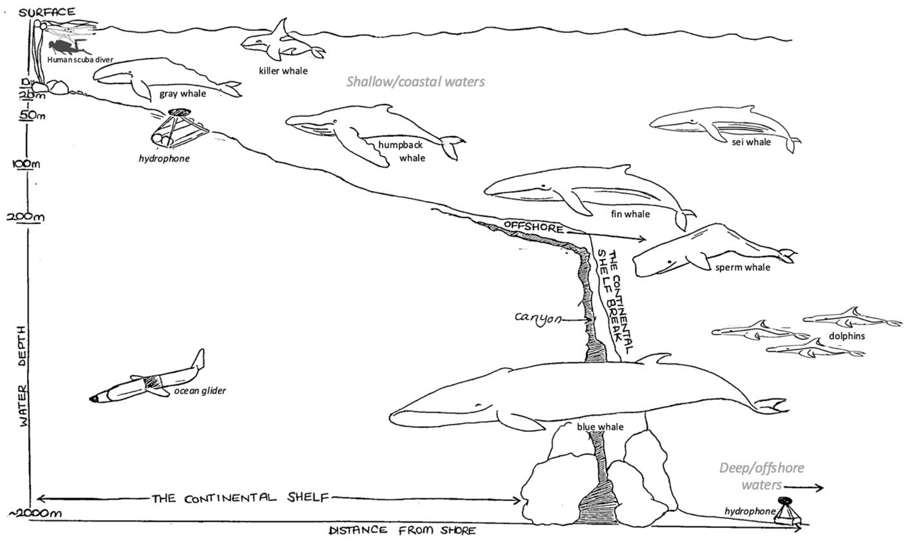

Figure 3

Figure 3

Ocean depths and locations where whale species were most heard by the hydrophones and the glider during the surveys. You can see the gentle slope of the continental shelf, the sharp drop of the continental shelf break, and the cracks in the shelf break that form canyons (this drawing is not exactly to scale).

After the excitement of the first glider survey, we prepared for our second, this time in the winter! For this survey, we wanted to further explore the canyon cracks of the continental shelf break (Figure 1, blue line), because we heard lots of calls in this area in the spring. We were curious as to whether we would hear the same whales in the winter as in the spring. In the spring the fin, blue and sperm whale calls had been mostly in the offshore waters, and fin whales heard the most when the glider was surveying in canyons. On this second survey, we heard lots more calls. The general patterns were the same as the first survey, with gray and humpback whales heard when the glider was closest to shore, and the bigger whales recorded in the deepest waters. We even heard sperm whales hunting! When hunting, their clicks get closer and closer, until they form a "buzz," just before the whale catches the fish or squid it is chasing.

Once we knew where we were most likely to hear each whale species, the next step was to understand what the whales were doing when we heard them, and if the areas off Vancouver Island are important to them. Calls used during feeding were heard from fin and blue whales (Figure 2) in the spring and from sperm whales all year round. Mating "song" calls were heard in the winter from male fin whales to attract females [1], and travel calls were heard from gray whales as they migrated. This means that these areas of the ocean might be very important for whale survival.

SOUNDS FROM HYDROPHONE RECORDINGS CAN HELP SAVE WHALES

Using recordings from hydrophones is a very good way to get information about whales. Using these instruments, we can survey in bad weather and in the dark, which would be very hard or impossible if we were in a boat or plane. But there are a few things we cannot tell just from listening to hydrophone recordings. When we hear a call, we know there is a whale in that location, but unless we hear lots of calls together, we do not know whether there is more than one whale. Also, hearing lots of calls does not mean there are lots of whales, we could just be listening to one very chatty whale! Whales might not call as much when they are eating and they may call more when they are trying to find other whale friends or a mate.

We heard thousands of whale calls in our experiments, and this told us when and where whales were and, in some cases, what they were doing, but there may be many more whales that we did not hear. The more surveys we do, and the more we listen to the oceans, the more we will know about whales and how they use these areas. Protection of these areas of the oceans might help whale numbers grow and species to survive. For example, areas that are important to the whales could be conserved as sanctuaries or marine protected areas or, for species closer to shore, rules about boating near whales may reduce the disturbance caused by humans. In general, our work and the work of other scientists can help conservationists and decision makers establish ways to protect whales, so that they will be around and healthy for many years to come.

ORIGINAL SOURCE ARTICLE

Burnham, R. E., Duffus, D. A., and Mouy, X. 2019. The presence of large whale species in Clayoquot sound and its offshore waters. *Cont. Shelf Res.* 177:15–23. doi: 10.1016/j.csr.2019.03.004

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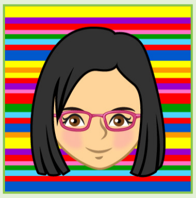

JUNIPER, AGE: 10
I like reading and coding. I also like animals. My favorite subjects in school are mathematics and art. My favorite art activities are paper marbling and modeling clay.

AUTHOR

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Dr. Rianna Burnham is an ecologist who uses passive acoustic monitoring techniques to add to what is known about marine ecosystems. She currently works as a research scientist for the Department of Fisheries and Oceans Canada. She has worked for more than 10 years on the west coast of British Columbia studying the behaviors of and habitat use by whales, and has increasingly become interested in how science can inform conservation and management actions. *rburnham31@gmail.com

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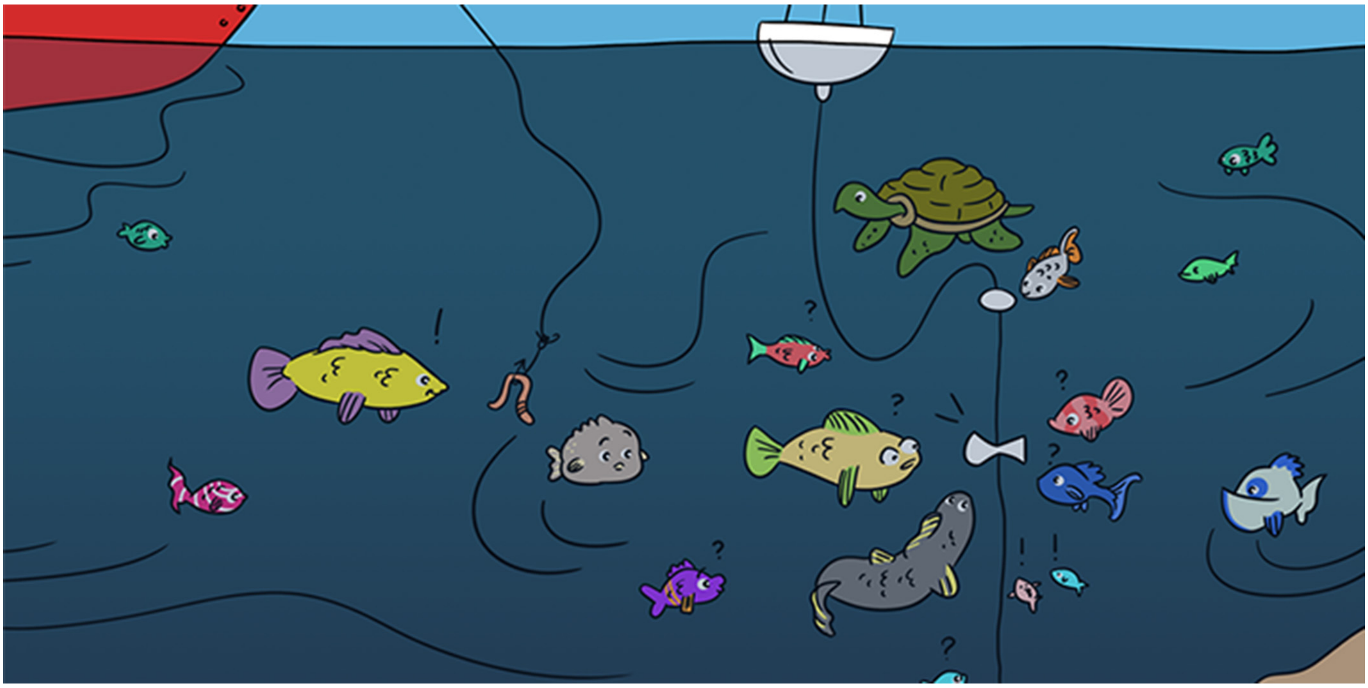

HOW DO WE CHOOSE TECHNOLOGIES TO STUDY MARINE ORGANISMS IN THE OCEAN?

Emmanuel Boss [1*] ***and Sasha J. Kramer*** [2]

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STEVENSON MIDDLE SCHOOL

AGES: 12–13

The organisms that live in the ocean range in size and type from microscopic plankton that use sunlight to produce energy to large whales that eat other microbes and animals for fuel. These organisms coexist in a vast ocean that covers nearly three quarters of the Earth's surface. Scientists who study the ocean face a challenge when they try to count and describe all of these different types of organisms: how can they choose the right tools and technologies to accurately measure these organisms and their environments? When scientists consider which tools and technologies to use to answer their questions about the ocean, they have to balance the cost of the measurement with the information they will get from the measurement. Here, we describe some of the different methods that scientists might use to study living things in the ocean, from nets or bottles used to collect water samples that are brought back to the boat or the laboratory, to robots that swim up and down and collect information about the deeper ocean, to remote satellites that send

signals back to Earth about the surface of the ocean. There are even ways for kids to get involved and help with ocean observation!

ORGANISMS IN THE OCEAN ARE DIFFICULT TO STUDY!

The ocean covers more than 72% of the Earth's surface and averages about 3,700 m in depth. How could we ever attempt to study such a large volume of water that contains so many different living things?

Oceanographers (scientists who study the ocean) use a number of different tools to study the ocean, spanning from **satellites** that can observe the ocean's surface daily, to research vessels (there are currently about 400 vessels operated by 50 different countries [1]), to **robots** that sink and rise periodically and are equipped with **sensors** (there are about 5,000 robots in use now). Most of these tools measure physical properties of the ocean, like the temperature and saltiness of the water, with nearly one in ten also collecting information about life in the ocean.

The ocean contains organisms of all sizes, from tiny organisms of 0.2–20 μm that are too small to see with our eyes (1 μm is one millionth of a meter, m), such as bacteria, most **phytoplankton**, and small **zooplankton**, up to larger organisms of 0.2–20 m, such as most fish and marine mammals. The mass of the tiny organisms is approximately the same as the mass of the organisms we can see [2]—there are lots of tiny organisms in the ocean! For example, in a teaspoon of ocean water, there are about 5 million bacteria and about 250,000 phytoplankton (organisms that use light to grow), and possibly one large zooplankton (zooplankton eat other organisms; some look like the character "Plankton" on Spongebob). The size difference between zooplankton and bacteria is like the size difference between the Eiffel Tower and a human! While tiny bacteria can multiply every few hours, large zooplankton need to find a mate to reproduce and live for about a year.

SATELLITE

An object in space that rotates around the Earth and on which sensors can be attached to observe the Earth.

ROBOT

An object that has some control of its own motion and on which sensors can be attached.

SENSOR

An object with electronic components that records signals generated from the environment around it.

PHYTOPLANKTON

Microscopic, single-celled organisms that use sunlight, dissolved gases, and nutrients for energy and to build cellular material.

ZOOPLANKTON

Animals that eat microbes for energy and to build cellular material.

DIFFERENT METHODS ARE NEEDED TO STUDY DIFFERENT OCEAN ORGANISMS

Since the organisms that live in the ocean come in many sizes, from very tiny to very large, oceanographers cannot use the same methods to study all ocean organisms. For example, tiny phytoplankton, which are found everywhere in the sunlit ocean, are the source of energy for the marine food web. Phytoplankton serve as food for other organisms and thus are important to study. But oceanographers cannot study phytoplankton the same way that they would study a top predator like an Orca whale, for example. While phytoplankton are always everywhere in the sunlit ocean, there may only be a single whale in

Figure 1

A color photo of the ocean taken from a satellite, showing swirls and eddies with widely different concentrations of chlorophyll a, a pigment shared by all phytoplankton. The areas that are greenest represent areas with more chlorophyll a, hence more phytoplankton. The text below the photo describes the large differences in concentrations of the various types of planktonic organisms present in one teaspoon of ocean water. The satellite image is from: https://oceancolor.gsfc.nasa.gov/gallery/.

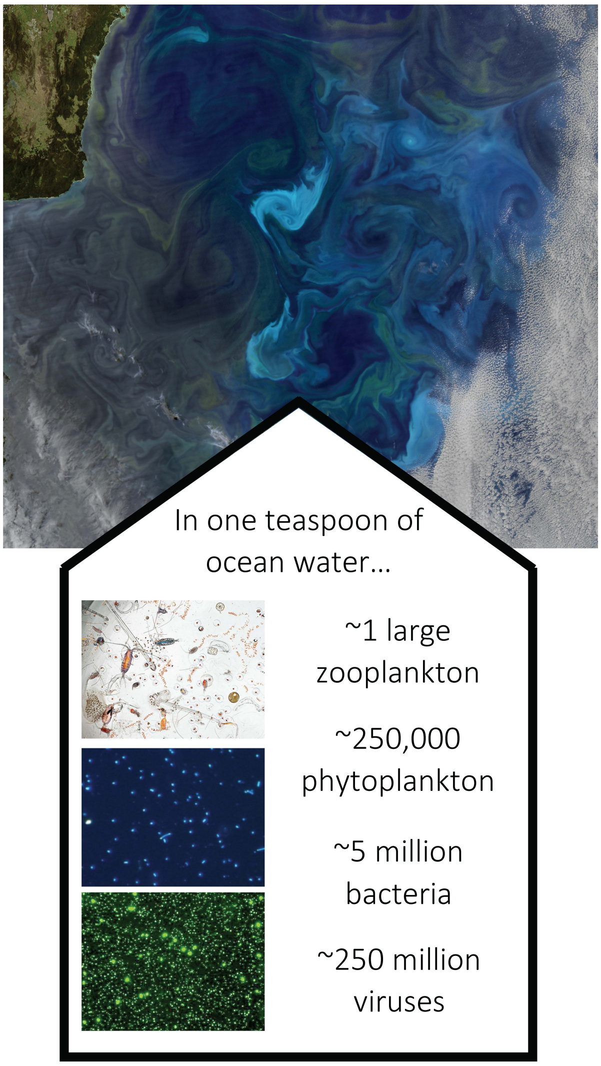

Figure 1

a whole bay at any one time. Phytoplankton are too small to count with our naked eyes, but a large whale would be easy to spot without any other tools.

To study the smallest organisms, such as bacteria, phytoplankton, and zooplankton, oceanographers use boats to collect water samples to study in the lab. They might look at these organisms with microscopes or use a special laser beam to figure out the number, size, and type of cells present in the sample. In the same way that humans might look at their own DNA to find out where their ancestors came from and what they might have looked like, scientists look at the genetic material of the organisms collected from ocean water samples to find out what type of organisms are in the water. To do this, scientists need to decode the genetic material to see if it matches other known organisms whose genetic codes have been previously studied and put in a library of genetic codes.

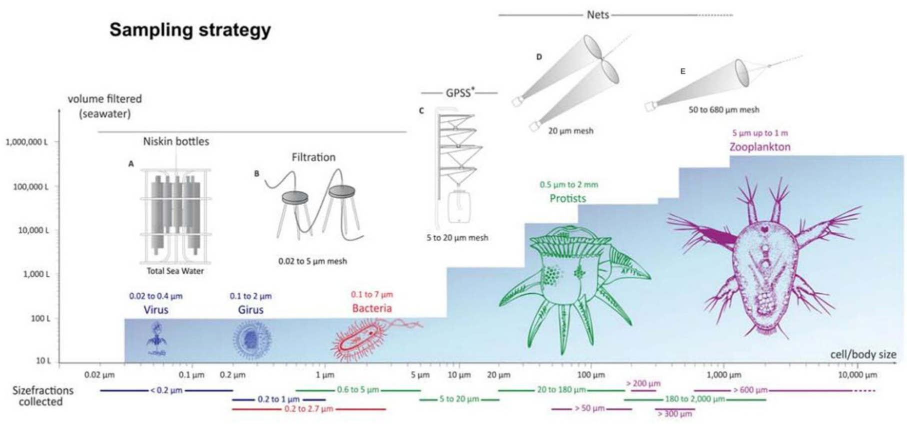

Figure 2

Figure 2

Different methods must be used to collect samples of ocean organisms of varying sizes. When we conduct a **holistic sampling**. Tiny organisms, like viruses, are collected using different types of filtration systems to remove them from ocean water. Zooplankton, which are more than a million times bigger than viruses, are collected using nets deployed in the ocean. This graph shows the amount of water (on the left axis) needed to be filtered to collect organisms of different sizes and types (on the bottom axis). Above the organisms, pictures of the specific filtration systems and water sources (whether bottles or nets) denoted with **A**–**E** are displayed. From Karsenti et al. [3].

HOLISTIC SAMPLING

A method of sampling where all part of a system of interest are sampled at the same time.

DNA can also provide information about the character of the organisms collected from the ecosystem—like whether or not the organisms can survive without oxygen. Water samples may also be analyzed for special substances contained in certain organisms. For example, oceanographers often look for a molecule called chlorophyll *a* in their water samples. Chlorophyll *a* is a pigment used by phytoplankton to collect sunlight for energy, just like trees do on land. The amount of chlorophyll *a* in the water is one measure of how many phytoplankton are in the water.

Phytoplankton in the surface waters of the ocean affect the color of the water (Figure 1). Satellites looking down on Earth take pictures of the surface of the ocean. Scientists use these pictures to map the distribution of phytoplankton. Even though they are too small to see with our eyes, a large number of phytoplankton (called a bloom) occupying a large area can clearly be seen from space.

To study larger organisms, such as the zooplankton that eat phytoplankton, scientists deploy cameras from research vessels, robots, or submarines. These cameras take pictures of the organisms present in the water. Ocean water is a good transmitter of sound. Oceanographers use acoustic sensors, which send a pulse of sound, and listen for its return, to map the distributions of zooplankton and fish. This method works because these organisms scatter the sound back to the sensor differently, depending on their size and shape. Listening for animal sounds is another way to study the distribution of organisms that produce sounds, such as whales. Whales have been known to "talk" to each other over thousands of kilometers!

Finally, nets are also used to collect organisms from different depths (Figure 2). This method is similar to the way a fishing boat catches fish in the ocean. The nets have a mesh, which is made up of many holes stitched together. Depending on the size of the holes, different marine

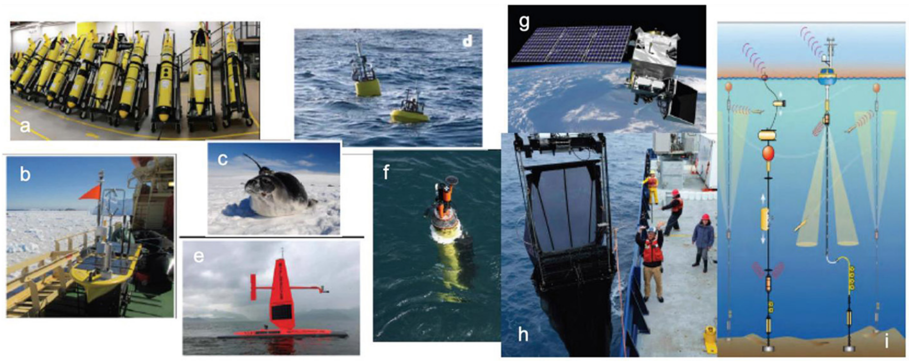

Figure 3

Figure 3

Examples of sampling platforms. Autonomous (independent) platforms include Gliders **(a)**, wave gliders **(b)**, marine organisms with attached sensor, such as seals **(c)**, Surface drifters **(d)**, sail drones **(e)**, and profiling floats **(f)**. All of these contain sensors to study the ocean and have no motor (the sensors and communication devices are powered by batteries). Satellites monitor the energy reflected or emitted from the Earth **(g)**. Ships with nets and other sampling system collect samples for lab analysis **(h)** while fixed mooring instrumented with sensors collect data at their location **(i)**. Photo credits for figure: **(a)** ALPS II report (https://alps-ocean.us/documents/). **(b)** A. Snyder, in ALPS II report. **(c)** D. Costa, in ALPS II report. **(d)** ALPS II report. **(e)** Saildrone Inc., in ALPS II report. **(f)** E. Boss, University of Maine. **(g)** NASA PACE project photo gallery (https://pace.oceansciences.org/gallery.htm). **(h)** NASA PACE project photo gallery (https://pace.oceansciences.org/gallery.htm). **(i)** https://oceanobservatories.org/.

organisms are caught in the nets, varying in size from phytoplankton to large fish.

ROBOTS CAN BE USED TO COLLECT DATA FROM THE OCEAN

Traditionally, oceanographers studied ocean organisms using boats equipped with nets and water collectors (large bottles that can close at a given depth, so water from the deep ocean can come up to the surface undisturbed). Also, automatic sensors can be deployed from ships or from robots. Like different types of boats, marine robots use different strategies to move around. Some marine robots move using motors, some have sails, and some change their depth in the water by changing their buoyancy (whether they sink or float). Currently, there are thousands of these marine robots roaming around the ocean (for pictures of some of them see Figure 3), many of which send their data back to shore through satellites. In this way, oceanographers can observe the ocean while staying on shore.

To understand why the numbers of some organisms vary in different parts of the ocean, oceanographers collect a variety of data from the environment. These data include the water temperature and amount of light at the depth where the sample was collected, the presence and amount of predators, as well as the presence of chemicals that may affect the organisms. Some of these chemicals, like dissolved nutrients, are beneficial to phytoplankton, and act like fertilizer does for plants on land. Others, like those chemicals that make the water acidic, may be bad for organisms. In acidic water, some organisms will have a hard time building a shell, for the same reason a tooth dissolves in a glass of Coca Cola.

To study the interactions between the organisms present in a certain area of the ocean, oceanographers need to take a holistic sampling approach. A holistic approach means that every part of the food web and the environment are considered together. To look at an area of the ocean holistically, all parts of the food web need to be measured at the same time. For instance, if oceanographers determine that phytoplankton in a certain area have enough light and nutrients to grow, it would be difficult to explain why the number of phytoplankton was not increasing, unless there are also measurements of the number of herbivores that are eating the phytoplankton as they grow.

CHALLENGES TO STUDYING MARINE ORGANISMS

Because the ocean is so large and because it changes over time, studying marine organisms can present many challenges for oceanographers. One difficulty that scientists run into when trying to study the ocean is called biofouling. Biofouling happens when organisms colonize (start to grow on) sensors and sampling platforms, resulting in bad measurements. Organisms in the ocean are often looking for a surfaces to grow on, and oceanographic sensors provide a perfect place for seaweed or barnacles to grow.

Another difficulty is the fact that organisms, such as fish are attracted to structures or lights in the ocean, which might possibly affect the measurements from those instruments. Fisherman know that the fish are attracted to these places, and will come to fish near ocean moorings. This effect demonstrates a challenge in oceanography: when we measure the ocean, we sometime change it.

Because the amount of money available to do oceanographic studies is limited, scientists need to think carefully about the questions they are asking and how they can get the right information to best answer these questions. A good scientific study will consider the characteristics of the organisms of interest. Oceanographers may ask questions like:

- How much water should I analyze to know the concentration of Organism X? If I only count one bucketful of water, will I get enough organisms to guess how many organisms are in this whole bay?
- For how long will the measurements I made hold true? If I took this sample 1 week ago, are the same organisms still in the water today, or have their numbers changed?
- How much of the ocean does this measurement represent? Can I say something about the whole ocean with my measurement, or just about the bay that I studied?

Answering questions like these is key to deciding how much, how often, and how far apart measurements should be made. This strategy will ensure that research money is well spent. The good news is that developments in technology over the years have helped drive down the costs of some of these measurement methods, as well as increase the amount of information oceanographers can gather from one measurement. If scientists cannot answer their research questions without a specific measurement and this measurement can only be made from a boat, then they should ask for time and money to go to sea on a research vessel. But maybe their question can be answered using satellite data that is collected every day all over the globe and a boat is not needed. This solution could possibly save money.

HOW CAN WE IMPROVE MEASUREMENTS OF ORGANISMS IN THE OCEAN?

To further expand ocean measurements, scientists need help. Some recent programs have non-oceanographers (including kids) taking measurements of the ocean. These "citizen science" programs have the potential to greatly increase our ability to sample the ocean. Many people care deeply for the ocean—they love going to the beach, swimming in the ocean, and appreciating the animals that live in the sea. The ocean is enormous, and there are only so many oceanographers (including the robots!) that can sample the ocean at a time. So, we need the help of people who care about the ocean to collect samples and share observations about the sea. Useful data can even be gathered by surfers (https://smartfin.org/)! If you are interested to join such a citizen science program, to help oceanographers collect data about the sea, take a look at the following links to see how you can help!

https://oceanservice.noaa.gov/citizen-science/ or

https://planktonplanet.org/ or

https://www.whoi.edu/what-we-do/educate/k-12-students-and-teachers/resources-for-teachers-citizen-science-projects/ or

https://medium.com/@TheW2O/citizen-science-and-the-ocean-4dff1b7e0d84

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

YOUNG REVIEWERS

STEVENSON MIDDLE SCHOOL, AGES: 12–13
The classes which reviewed this article are comprised of in total 63 seventh grade science students in the beautiful State of Hawaii. We are two classes of inquisitive minds and strong opinions who are working to sharpen our critical thinking skills while expanding our world view through the lens of science!

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Emmanuel is an aquatic physicist who develops methods to study the amount and characteristics of different materials in water (for example phytoplankton and sediments). He uses sensors deployed on satellites, on robots, strapped to fixed structures, or lowered from ships and compare their readings to laboratory analysis of what is in the water. Together with a student, he developed an App to measure water turbidity from smartphones. He is happiest when he is immersed in water (he is an avid diver and swimmer). *emmanuel.boss@maine.edu.

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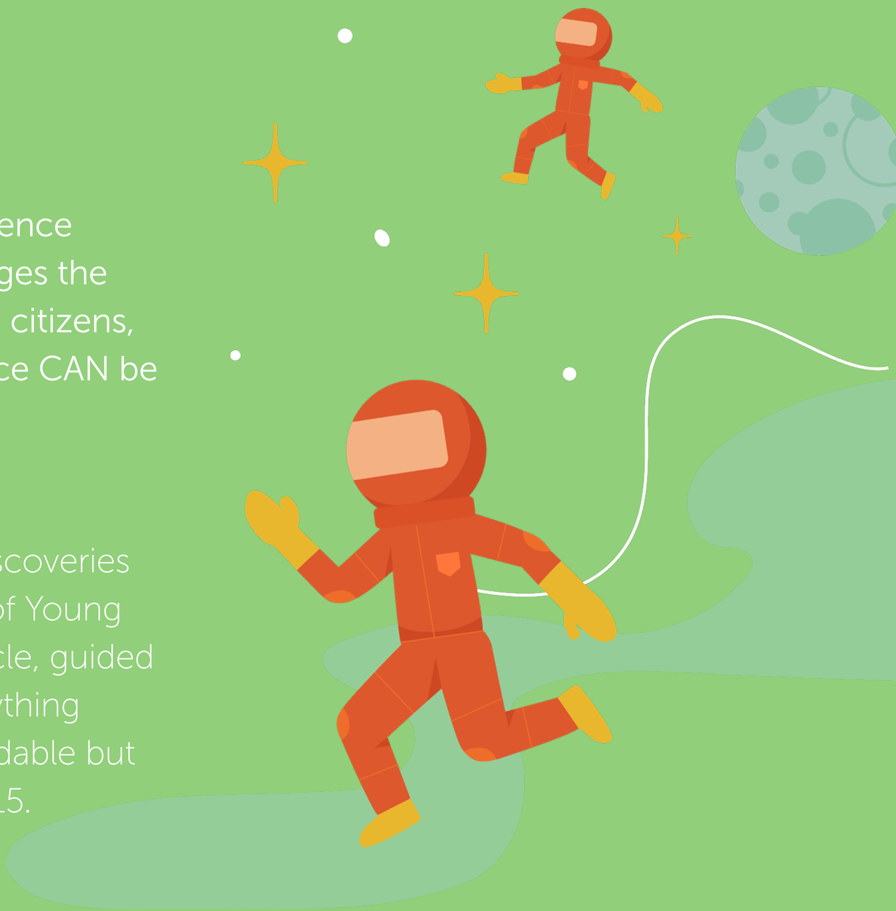

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