Glacier Ice: A Museum of Ancient Microbes

Grandfather: we heard today that there are microbes in glaciers. They must be even older than you!

Ice core drilling and ice core; Photo credit: Lonnie G. Thompson/The Ohio State University

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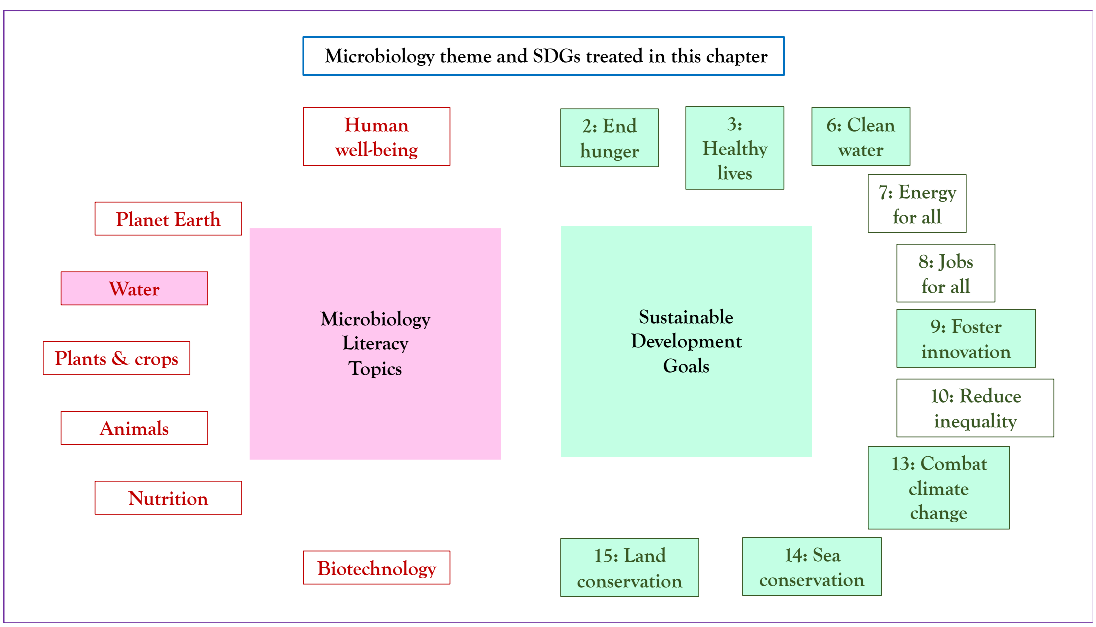
Glaciers

Storyline

Glaciers are found in high-elevation mountains and the two polar regions. They cover 11% of the land and store 70% of the world's freshwater. Glaciers grow from the snow that falls on them year after year but does not melt during summer. Glaciers serve as museums of ancient climates and microbes, and allow scientists to explore past climates and the evolution of microbes over thousands of years. Ancient microbes could serve as sources for biotechnological innovation (e.g., food industry) and help us search for and interpret signs of life on other frozen worlds beyond Earth. However, glaciers are now rapidly melting and releasing the preserved water and ancient microbes, and exposing the soil underneath. The water can cause flooding, erosion, and sea-level rise, and reduce the reliability of water for drinking, irrigation, and hydroelectricity for billions of people. The released microbes and viruses could include ancient pathogens and potentially genes that do not exist today. The newly-exposed soil can be washed into waterways and disturb downstream ecosystems and accelerate climate warming. Collectively, melting glaciers relate to many of the UN's Global Sustainable Development Goals. Thus, the study of glaciers is urgently needed to uncover the wealth of information they archive about our past. In parallel, we need to implement actions to slow climate change and thereby help reduce glacier melting and thereby contribute to the preservation of these microbial museums.

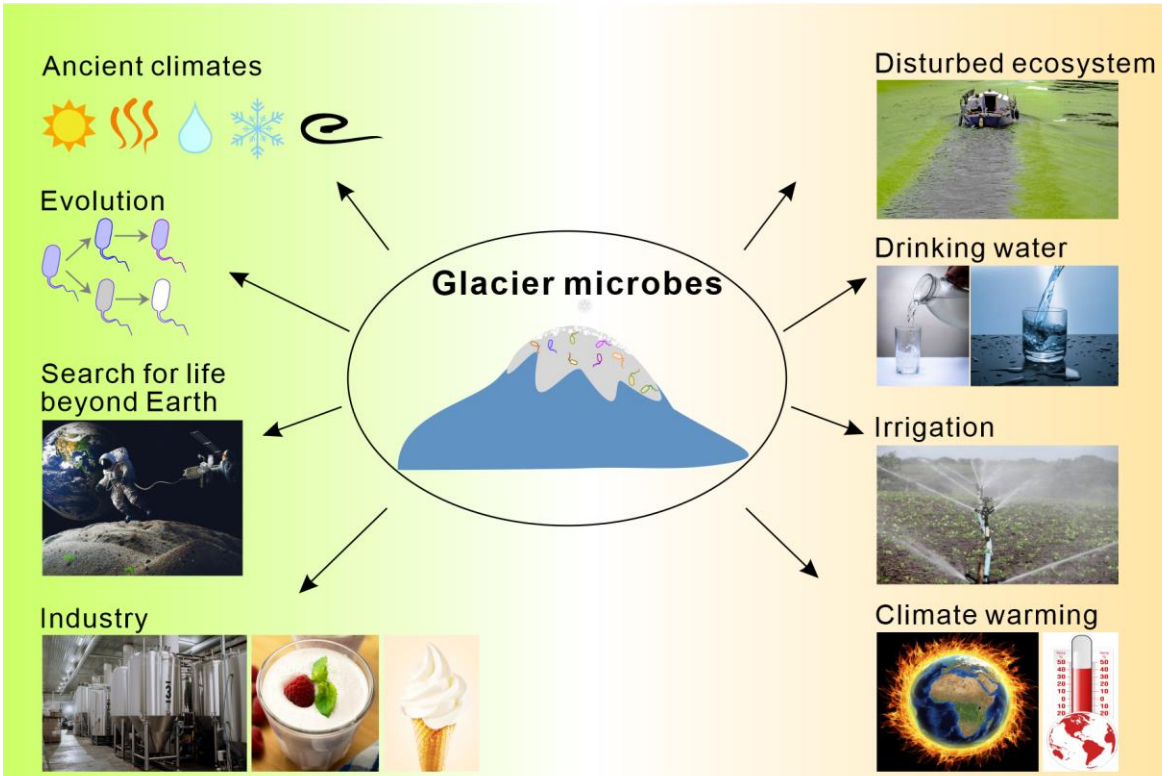
The Microbiology and Societal Context



The microbiology: ancient microbes; ancient climate histories; evolution of life; applications; pathogens and health; search for extraterrestrial life; modern ecosystem disturbances; freshwater stores; greenhouse gas production. *Sustainability issues include:* food production; health; drinking water; industrial usage; climate warming; and disturbance of life in the water and on land.

Glaciers: The Microbiology

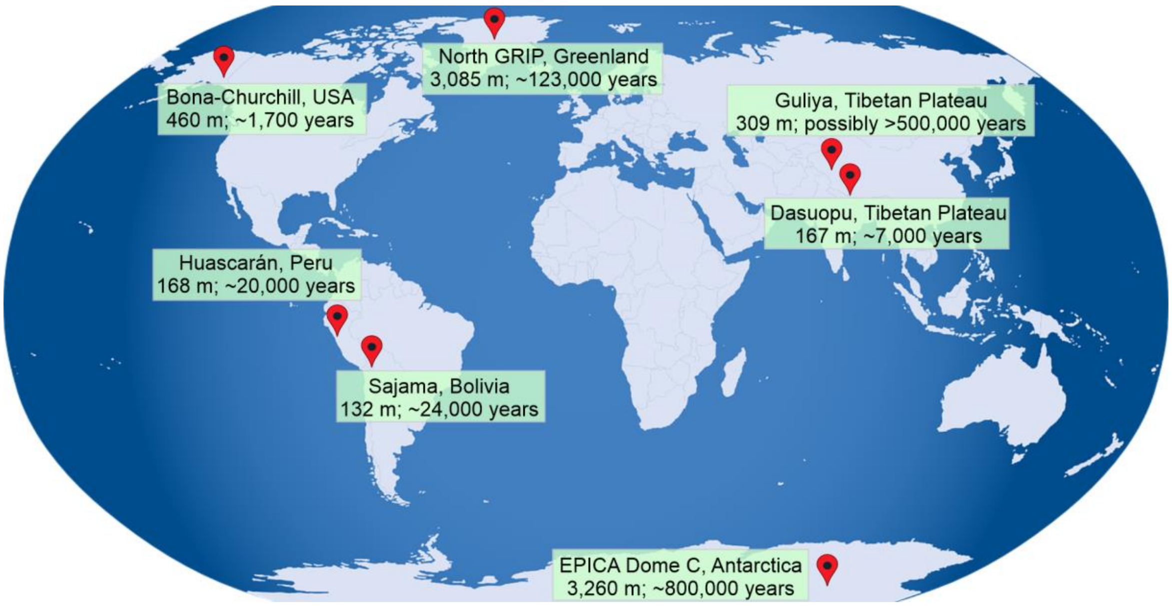
Utilization of glacier microbes and impacts of glacier melting



1. ***Glaciers are great museums of the past, including ancient climates and microbes.*** Today, glaciers and ice sheets cover about 11% of our planet's land. Many years ago, during warmer climates, the land where glaciers now sit was covered with grasses, forests, deserts, or plains. As conditions got colder, glaciers gradually formed in places where the snow did not melt completely every summer, so that year after year the snow continued to get thicker. Eventually, as the snow grew so thick that it was compressed into ice, it began to move and formed a glacier that grew as more snow fell on the top. Together with the snow, pollen, dust, and microbes also fell onto the glaciers, and air was trapped inside bubbles that are preserved in the ice. Sometimes bigger things, such as leaves or insects are also preserved in glaciers, but this is rare!

Thus, glaciers are great museums for ancient climates and organisms, including microbes. Imagine an ice core drilled from the surface to the bottom of a glacier: it would contain information about climates, plants, and microbes over the entire life of the glacier which could be hundreds of thousands of years. Thus, glaciers are windows into the past, including ancient climates, volcanic eruptions, the composition of our atmosphere trapped in bubbles, and microbes.

Length and bottom ice age of seven ice cores



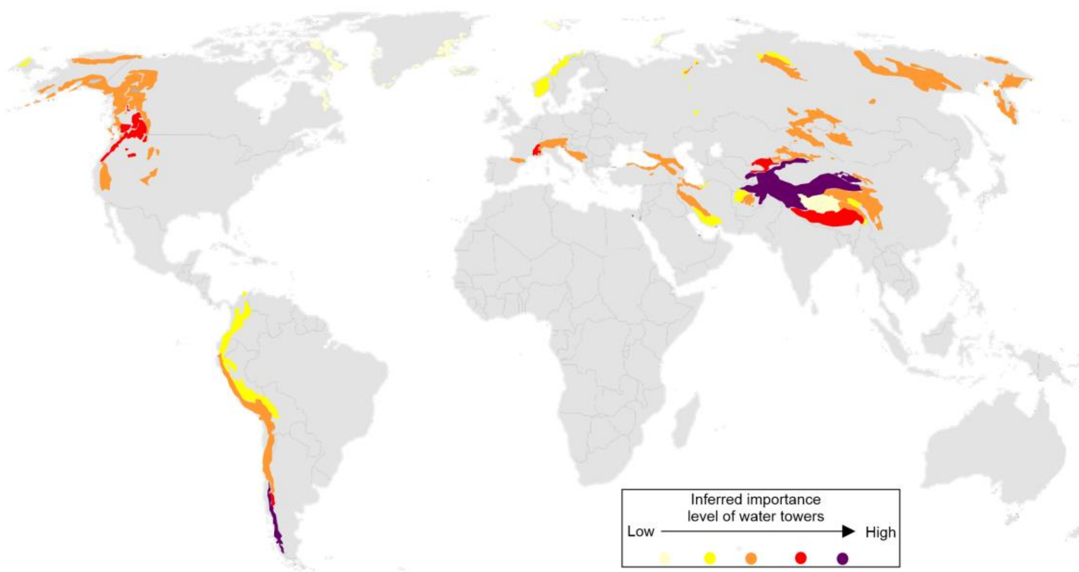
Ice core length versus age: The length of an ice core from the surface to the bottom of a glacier does not always indicate the age at the bottom of the glacier. In other words, the longest core (from the thickest glacier) is not always the oldest core. For example, the ice cores from Antarctica and Greenland are both about 3,000 meters (9,843 feet) to bedrock, but the EPICA Dome C core (3,260 meters) in Antarctica contains ~800,000-year-old ice while the North GRIP core (3,085 meters) in Greenland only contains ~123,000-year-old ice. The average annual accumulation (e.g., snow deposition minus melting) and temperature are major controls on the number of years contained in the ice sheet at those locations. For example, compared to Greenland, much of Antarctica typically has lower accumulation rates and colder temperatures and thus archives older ice in a core of nearly the same length as that in Greenland.
(GRIP, Greenland Ice Core Project; EPICA, European Project for Ice Coring in Antarctica.)

2. ***Glacier microbes can tell us about evolution over many thousands of years.*** Our human ancestors - the very first of our *Homo sapiens* species - appeared on Earth about 300,000 years ago, while microbes have existed for at least 3.7 billion years (3,700,000,000 years!!). They are the earliest life forms on our planet! Scientists believe that humans, animals, plants, and all other life forms evolved from microbes. Like humans, today's microbes also have ancestors. The glaciers are museums of those "ancestor" microbes which can help us understand the mystery of how microbes and other life forms have evolved over the past hundreds of thousands of years.

3. ***Melting glaciers impact humans' access to freshwater.*** Since glaciers and ice sheets contain about 70% of Earth's freshwater, they are important freshwater reserves - like the water storage towers of the planet. For example, more than 1.5 billion people - which is nearly 20% of the world's population - rely in part on meltwater from the ~4,600 glaciers located in the Tibetan Plateau - people call it Earth's "***The Third Pole***" (joining the North and South Poles as a distinct area of planetary importance; see Section "Glossary"). This mountainous cold icy area is very important to 12 Asian countries: Afghanistan, Bangladesh, Bhutan, China, India, Kazakhstan,

Kyrgyzstan, Myanmar, Nepal, Pakistan, Tajikistan, and Uzbekistan. People in this region, and in others near glaciers from the European Alps to the South American Andes, regularly use seasonal glacial meltwater for drinking and irrigation.

Global glacier-supplied Water Towers



Importance level of water towers: The importance of global water towers is indicated by five colors, which ranks all water towers in terms of their water-supplying role and the downstream dependence of ecosystems and society. For example, the most important water towers are indicated in purple. **Figure credit:** Yuan Zhou/The Ohio State University made this plot according to a figure published by Immerzeel and co-authors in *Nature* (www.nature.com/articles/s41586-019-1822-y/figures/1).

Some countries also use glacier meltwater to produce electricity by means of hydroelectric power plants. However, global warming is changing these glaciers quickly. The globally averaged thinning rate for glaciers (excluding the Greenland and Antarctic ice sheets) has doubled in less than 20 years! In 2000, the average thinning rate was 36 cm/year (~14 inches/year), but by 2019 it was 69 cm/year (~27 inches/year). This means that in some cases the meltwater for humans living nearby is increasing, and that can also cause serious flooding. However, as glaciers shrink or disappear, the amount of meltwater will decrease and become less predictable, and thus many people will face water shortages in the future.

4. ***Glacier melting can disturb ecosystems.*** From studies of glaciers around the world, scientists estimate that Earth's glaciers contain approximately 10^{23} – 10^{27} microbial cells - that is one hundred to one million times as many known stars as in the universe! Unfortunately, as glaciers melt, ancient microbes are being released to local environments including soils, rivers, lakes, and oceans. Since microorganisms can share genes, the genes released from ancient microbes and viruses may mix with modern genes to produce microbes that may represent types not seen before. The microbes released and the new microbes they create might disturb the ecosystems they enter - for example by competing for food with indigenous microbes.

The glacial meltwater eventually reaches the oceans and has contributed to about 21% of the observed sea-level rise during 2000-2019. Roughly 200 million people live on land that is predicted to be below the high-tide line by the end of the 21st century, and some coastal communities are already relocating to higher ground.

Freshwater released from glaciers will dilute the salinity of ocean water which can alter its circulation patterns in ways that further modify Earth's climate, and they may also disturb ocean ecosystems.

In addition, the released ancient microbes (or new ones they create) might be pathogens that affect plants, animals, or humans. It is possible, though not likely, that certain microorganisms originating from melting glaciers could make freshwater sources less safe to drink, hurt native wildlife or livestock, or even affect humans directly.

5. ***Glacier melting can also impact global warming.*** As glaciers melt, the soil beneath them is freshly exposed to the elements and erosion.

> ***Did you know that the carbon in the Earth's glaciers and their basal environments is more than that in all the lakes and rivers combined?***

Since glaciers cover 11% of Earth's land areas, there is much soil and carbon to be potentially uncovered for the first time in centuries! Microbes in that old soil, and in the surrounding systems where they enter, can eat this carbon and convert it into greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which warm our planet and further enhance climate change. They can also convert nitrogen sources to nitrous oxide (N_2O), another powerful greenhouse gas.

6. ***Glacier microbes are potential industry resources.*** Ancient microbes could be sources of novel, useful genes for our factories and industries. Microbes preserved in glaciers have likely lived under various conditions (e.g., low nutrient, high radiation, high desiccation, high elevation, cold temperature, etc.) and so their enzymes may be able to work under different conditions, too. Additionally, some of these microbes also lived and reproduced in the layers of snow on the top of glaciers as they were adapted to cold temperatures and harsh conditions.

Some of these microbes and their genes can help us solve human problems in cold environments today such as providing more effective wastewater treatment and cleaning up polluted soils in cold regions. Some of the cold-adapted microbes produce ***ice-binding proteins*** (See section "Glossary") that can influence the growth of ice crystals.

They also have been used in the food industry for many things, including ice cream production and cold storage of yogurt and meat.

> ***Did you know that the next time you enjoy an ice cream cone, you might have a cold-adapted microbe to thank? What if glacier microbes have new kinds of ice-binding proteins that could allow the next generation of food scientists - maybe you - to mix new flavors and make new ice creams that could not previously be frozen?***

Ice-binding proteins can also be used for producing artificial snow. If you watch the Winter Olympics, you know how increasingly important artificial snow has become due to the warming climate. New microbes might allow us to prolong our participation in our favorite winter sports.

Moreover, *ice-binding proteins* have the potential to be used in medicine to help preserve organs for transplants. They may also assist in cryosurgery, a special kind of surgery performed under cold conditions and which requires new natural methods for the storage of tissues and organs at low temperatures.

7. ***Glacier microbes may help with the search for life beyond Earth.*** There are scientists who search for life on other planets - they are called *astrobiologists*! In their search, they prioritize finding liquid water, since it is an essential requirement for life on Earth. Water allows chemicals to dissolve and move around, so astrobiologists think it is also likely to be a requirement for life anywhere in our universe.

They have found several other places in our solar system with ice, including Mars, Jupiter's moon Europa, and Saturn's moon Enceladus. So developing methods to explore and understand microbes in Earth's glaciers likely offer tools for the search of extraterrestrial life.

Planets with water ice in the solar system

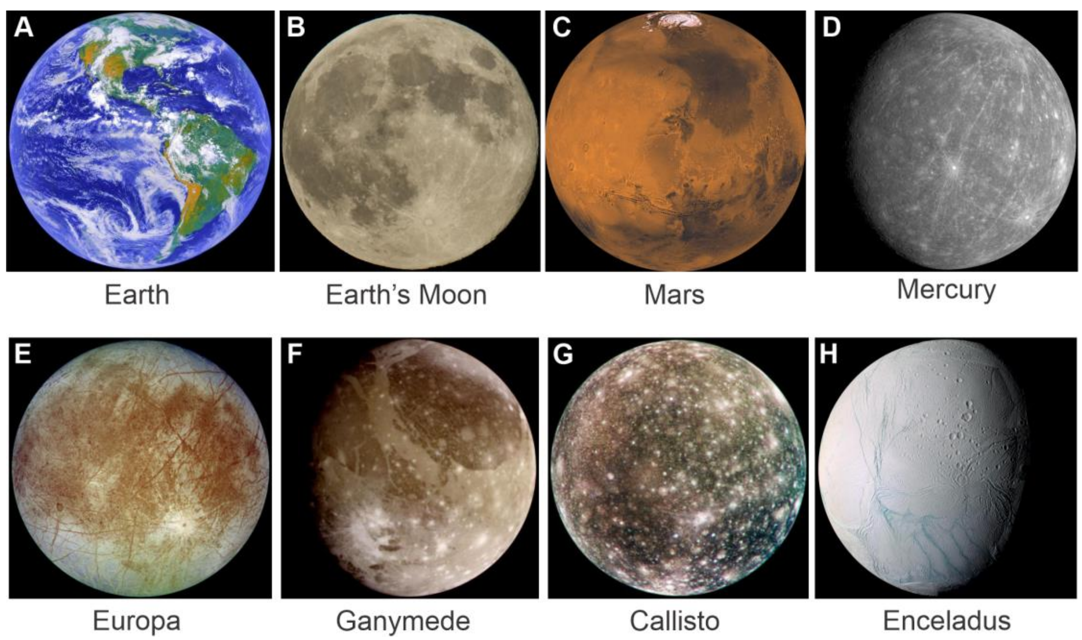


Photo credit: A via NASA (https://images.nasa.gov/details-0202795); B via NASA/Bill Ingalls (https://images.nasa.gov/details-201408100002HQ); C via NASA/JPL/USGS (https://images.nasa.gov/details-PIA00407); D via NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington (https://images.nasa.gov/details-PIA11245); E via NASA/JPL/DLR (https://images.nasa.gov/details-PIA00502); F via NASA/JPL (https://images.nasa.gov/details-PIA00716); G via NASA/JPL/DLR (https://images.nasa.gov/details-PIA03456); H via NASA/JPL/Space Science Institute (https://images.nasa.gov/details-PIA06253).

One of the important missions for the NASA Mars rover, *Perseverance*, which was launched in 2020, is to seek evidence of ancient microbial life. Whether life as we know it is unique to Earth is one of humanity's most profound questions! *What do you think about this?*

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2. Hunger.** Seasonal glacial meltwater feeds many major rivers around the world and is used for irrigation of crops and water for livestock. Less predictable meltwater release, and the potential for eventual reduction or total loss of meltwater, will have a large impact on regions that use this natural resource for food production. As glaciers melt, greater flooding is expected which may cause significant crop and livestock losses. Moreover, lakes and streams that are fed by glaciers and provide habitats for freshwater fish that serve as a protein source for millions of people, may diminish or disappear. The discharge of fresh (i.e., not salty) meltwater from the large ice sheets, Greenland and Antarctica, already appears to be changing ocean current patterns with the potential to impact marine fisheries, which provide roughly 17% of the protein for humanity globally. Lastly, the possible pathogens released by melting glaciers could impact crops, livestock, and fisheries. In these many ways, the loss of glaciers will contribute to food insecurity.
- **Goal 3. Health.** Water insecurity - unreliable access to clean drinking water - is associated with poorer health, worse sanitation, and more disease. For billions of people who use glacial meltwater, the loss of glaciers will likely decrease their health due to water insecurity. During the period when the glaciers are melting, the flooding and standing water can provide breeding grounds for mosquitos and pathogens. As mentioned before, glaciers may contain ancient pathogens that may be released upon melt. In these ways, the loss of glaciers threatens global health.
- **Goal 6. Clean water.** Glacial ice contains about 70% of the freshwater on our planet, which provides drinking water for billions of people. The stockpiles of freshwater currently locked up in glaciers are beginning to decline due to Earth's warming climate. See Goal 3 regarding water insecurity.
- **Goal 9. Industry & Innovation.** Ancient microbes could be sources of novel, useful genes for our factories and industries. For example, the cold-adapted microbes and their enzymes have been used for wastewater treatment, ice cream production, and cold storage for food and medicine. See Section 6.
- **Goal 13. Climate Action.** Glacier melting will expose the ground underneath and thus release the carbon that is stored there. This released carbon could be utilized by microbes to produce "climate warming" greenhouse gases. In addition, microbes released from glaciers could contribute to the production of greenhouse gases, thus accelerating climate warming. Today's rapid climate change is accelerating glacier melting. We need to implement actions to slow climate change to help reduce glacier melting and thereby contribute to the preservation of these carbon and microbial museums.
- **Goal 14. Life Below Water.** Melting waters from glaciers, and the associated erosion, will impact freshwater and marine ecosystems. Increased cloudiness of the water decreases plant growth (e.g., phytoplankton), and freshwater released to the oceans can alter the circulation patterns of its currents. It is worrisome that rising sea levels will result in submergence of some coastal waste disposal sites and the mobilization of their pollutants into marine systems, with the associated detrimental ecological consequences.
- **Goal 15. Life on Land.** Glacial meltwater supports animals and plants, but can also result in floods. As glaciers rapidly melt and discharge more meltwater, life forms on land are likely to be negatively impacted. With continued warming, the glaciers will shrink and the available

meltwater will then be reduced further stressing land-based plants and animals on which humans depend, especially in the dry season and during times of drought. Ancient microorganisms including potential agricultural, animal, and plant pathogens may be released into the environment with detrimental effects. On the other hand, as the land now covered by glaciers is exposed, new habitats will be available for life on land to colonize.

Potential Implications for Decisions

Glaciers are melting as a result of global warming: what can we do to minimize global warming?

1. ***Individual***
   a. What I eat – meat comes with a large carbon footprint, so eating less or no meat reduces your carbon footprint.
   b. What I eat – globally-sourced food comes with a large carbon footprint, so eating locally-produced food when in season, and not demanding food produced out of season, reduce your carbon footprint.
   c. How much food I waste – food production, transport, and storage consume energy. And, if it goes into a landfill, it contributes to greenhouse gas production. Can I minimize my food waste? When I do have food waste, can I compost it instead of putting it in a landfill?
   d. How much energy I consume – how hot and long are my showers? When it is cold inside, do I grab a sweater or turn on the heater? Do I turn off the lights when not needed? Do I use more efficient light bulbs?
   e. How I travel – do I walk, bicycle, use public transportation, or drive? Do I carpool when I must drive, and/or bundle errands to minimize trips? Do I travel by air if there is the possibility to travel by train?
   f. How I treat nature – plants consume the greenhouse gas CO_2; do I help protect green spaces? Do I plant trees?
   g. What my pet eats – meat comes with a large carbon footprint, so using alternative animal food made from vegetable and insect protein sources can reduce your family's carbon footprint.
   h. How many pets I have/how large they are – the amount of pet food we buy is proportional to the number of pets we have and their size.
   i. How I use my voice – do I talk to my friends and family about how we can decrease climate change? Do I speak up for politicians to make policy that helps with global warming?

2. ***Community policies***
   a. Incentivizing use of, and improving access to, public transport.
   b. Incentivizing local production – and consumption - of food.
   c. Providing municipal composting and recycling.
   d. Incentivizing tree planting and green space protection.
   e. Incentivizing energy efficiency retrofits to existing building and requiring it in new construction.
   f. Public education on carbon footprints in daily life, of the value of locally-produced food and of public transport.
   g. Public education on ways to save energy.

3. ***National policies***
   a. Reduction of greenhouse gas production through
      i. elimination of fossil fuel-based energy supply;
      ii. incentivizing solar, wind, and hydroelectric energy infrastructure development and use, as well as biohydrogen and, in future, bioelectricity energy sources;
      iii. Tax incentives for home energy efficiency retrofits;
      iv. Improving national and regional public transportation networks;
      v. Incentivizing use of public transportation;
      vi. Continued and expanded tax incentives for fuel-efficient and electric vehicles;
      vii. End subsidies for corporate meat producers, and provide funding and incentives for development-to-market and adoption of insect-based protein sources.
   b. Citizen education about global warming, glacier melting, greenhouse gases, etc.

Pupil Participation

1. ***Class discussion***
   a. Melting glaciers impact a number of the UN's Global Sustainable Development Goals. In your view, which are the most important, and why?
   b. If you could peer into the past using the organisms preserved in glaciers, what would you most want to know about how things were different where you live 10,000 years ago? What about 100,000 years ago?
   c. Glacier microbes are potential biotechnological resources for various industries, such as food and medicine. Can you envision other applications for which the glacier-preserved microbes might be used?
   d. Glaciers, could this be *Jurassic Park on Ice*?

2. ***Pupil stakeholder awareness***
   a. Glaciers are melting quickly today due to climate change. What can you do personally to slow climate change?
   b. Are there any glaciers in your country or region? Who uses water from these glaciers? Are there "climate resilience" plans for those who depend on this water?
   c. Does your country have coastal areas? Are those communities being impacted by rising sea levels yet? If so, how? What plans are there for helping those communities in the future?

The Evidence Base, Further Reading, and Teaching Aids

How were glaciers formed? https://www.youtube.com/watch?v=JJi5ICgmTsE

Ohio State Insights. 2019. Understanding Ice cores (a cartoon): https://www.youtube.com/watch?v=df_ExaG1uGg

PBS News. 2021. Glacier ice samples act as records of climate change's impact on Earth. https://www.pbs.org/newshour/show/glacier-ice-samples-act-as-records-of-climate-changes-impact-on-earth.

BPCRC. 2016. Ice core drilling on the Guliya Ice Cap. https://www.youtube.com/watch?v=UcwSonWRVlE&t=41s
Arenschield L. 2021. 15,000-year-old viruses were discovered in Tibetan glacier ice. https://news.osu.edu/15000-year-old-viruses-discovered-in-tibetan-glacier-ice/.
Ludacer R. 2018. How humans evolved from the first life - microbes. https://www.youtube.com/watch?v=2W5hOJaFjxU.
What if all the world's ice melt? https://www.youtube.com/watch?v=dEYJV9ApH5Q
Immerzeel W.W. et al., 2019. Global distribution of glacier-based water tower units: https://www.nature.com/articles/s41586-019-1822-y/figures/1
Top 10 places where life might exist beyond Earth: https://www.youtube.com/watch?v=ljBEjA7bMsY
Research publication for the EPICA Dome C core: https://www.science.org/doi/10.1126/science.1141038
Research publication for the North GRIP core: https://www.nature.com/articles/nature02805

Glossary

Ice-binding protein: The Ice-binding protein (IBP) includes two groups: antifreeze proteins (AFP) and ice-nucleating protein (INP):

AFP is a protein that can decrease the fluid's freezing point to avoid freezing. If ice crystals grow inside or around microbes, the crystals can injure them, or make survival more difficult. So some microbes that are adapted to life at cold temperatures make AFP that binds small ice crystals and keeps them from growing larger.

INP is a protein that can initiate ice crystal formation. Ice crystals can injure cells. Some microbes that have ability to live with ice make INP that create ice crystals which injure and break open plant cells and thereby provide microbes with access to nutrients in plant cells.

The Third Pole: The high-altitude and chilly area of Asia's Tibetan Plateau and the Himalayan Mountains is so important to regional and planetary atmospheric circulation and weather, and to humans living in the region, that it has been given the name "The Third Pole". It is an icy region with an average elevation >4000 meters above the sea level, and more than 46,000 glaciers. These glaciers contain the largest reserve of fresh water outside the two polar regions (i.e., the Arctic and Antarctic). The Third Pole is considered the "Water Tower" of Asia, as it feeds Asia's largest rivers and provides fresh water for more than 1.5 billion people in 12 Asian countries (Afghanistan, Bangladesh, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Myanmar, Nepal, Pakistan, Tajikistan, and Uzbekistan).