Life Within and On Arctic and Antarctic Sea Ice

Mom & Dad: Why are the effects of climate change on the ice in the Arctic and Antarctic Oceans important – is it just about polar bears and penguins?

When working on the microbiology of Antarctic sea ice floes,
curious penguins are rarely far away-like these Emperor penguins in the Weddell Sea.

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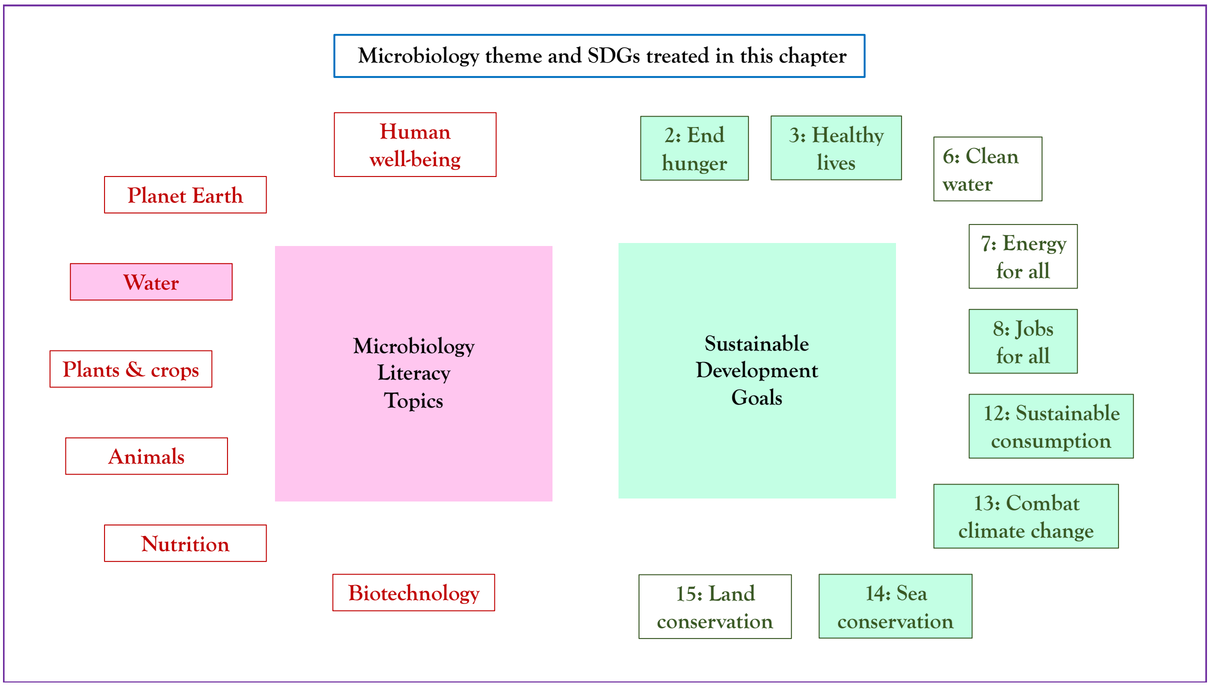
Storyline

The vast expanses of ephemeral frozen pack ice of the Arctic and Southern (Antarctic) Oceans are not *icescapes* devoid of life. Instead, the ice contains thriving microbial assemblages that are key components to the food-webs of these vast marine systems. The microbes undergo a dramatic phase shift in living conditions from the relatively well-buffered open water to a semi-solid ice matrix where changes in external stress factors can be harsh and rapid. Global climate change is having profound impact on the seasonal dynamics of sea ice, both in the quantity of ice formed and length of time it persists. This in turn will majorly impact the microbiology of the ice and its seasonal input into food webs that sustain an outstanding diversity of marine organisms (bacteria through to whales), some of which humans harvest for food.

The Microbiology and Societal Context

The microbiology: marine food webs; microbial diversity; stress biology. *Sustainability issues*: end hunger; health; sustainable food; healthy environments; climate change; sea conservation.



Polar Sea-Ice: The Microbiology

1. ***Phase shift from water to ice.*** Arguably there are 4 main abiotic (non-biological) factors governing where and when planktic (free-floating) micro-organisms inhabit different parts of the planet's surface oceans: light, temperature, available nutrients & the salt content of the water (its salinity[1]). The major oceans, regions of oceans or large ocean water masses are characterized, even identified, by having different characteristics based around annual ranges of these parameters. As far as temperature and salinity go, for most geographic regions the variation in these two parameters during the year are modest. This in turn means that the planktic micro-organisms living within a particular water mass are mostly exposed to modest changes in these two parameters.

a. Water freezing. However, in the Arctic and Southern Oceans there is an annual phenomenon where this generalization does not hold true. In the autumn, air temperatures fall causing surface waters to cool. The action of wind can mix this cooling from 10's to 100's of meters of depth. In seawater at around -2°C, freezing begins and ice crystals begin to form (N.B. The freezing point of seawater is colder than that of freshwater (salinity of 0) because of the salts contained within the seawater). As the ice crystals form, they expel the dissolved salts into the surrounding waters, thereby increasing the salinity of that water.

b. Grease ice. The ice crystals float to the surface of the ocean where they accumulate as a surface layer, commonly referred to as **grease ice**. It is called this because, when viewed from above, it sort of resemble slicks of oil on the ocean surface. Depending on how rapid the cooling, and how strong the prevailing winds these layers can be between 10 and 50 cm thick. So, within a very rapid period the surface of the ocean has been transformed from a salty liquid to a semi-solid slush of solid ice crystals suspended in a liquid that is saltier that the liquid below.

2. ***Formation of ice floes***

a. Pancake and Nilas ice. What happens next depends largely on the wind conditions as it gets colder. Where there is turbulence in the surface layer, the grease ice coalesces into disc-shaped accumulations of ice crystals called **pancake ice**. These grow from the outer edges into pancakes several meters in diameter. If the grease ice layers are not subjected to much water movement they freeze into continuous sheet of rather uniform flat ice, called **Nilas ice**.

b. Rafting, ice floes, ridges and leads. Both types of ice get thicker by **rafting** on top of each other and continued freezing of water under the ice, all combining to give **ice floes**, on average around 1 to 2 m thick. Ice floes can vary in size from just a few metres in diameters to 100's meters wide. Many floes can freeze together to form continuous ice floes up to several kilometres wide, which can then break up again into smaller floes as the ice moves with currents, tides and wind. When wind and currents force ice floes against each other they can raft on top of each other and form huge ice piles called **ridges**. Also, wind can pull them apart to expose open stretches of water called **leads**. Moving ice creates a landscape that changes day by day and even hour by hour. Where there is a lot of rafting of ice floes, dense accumulations of ice block can form pressure ridges several 10's of meters thick.

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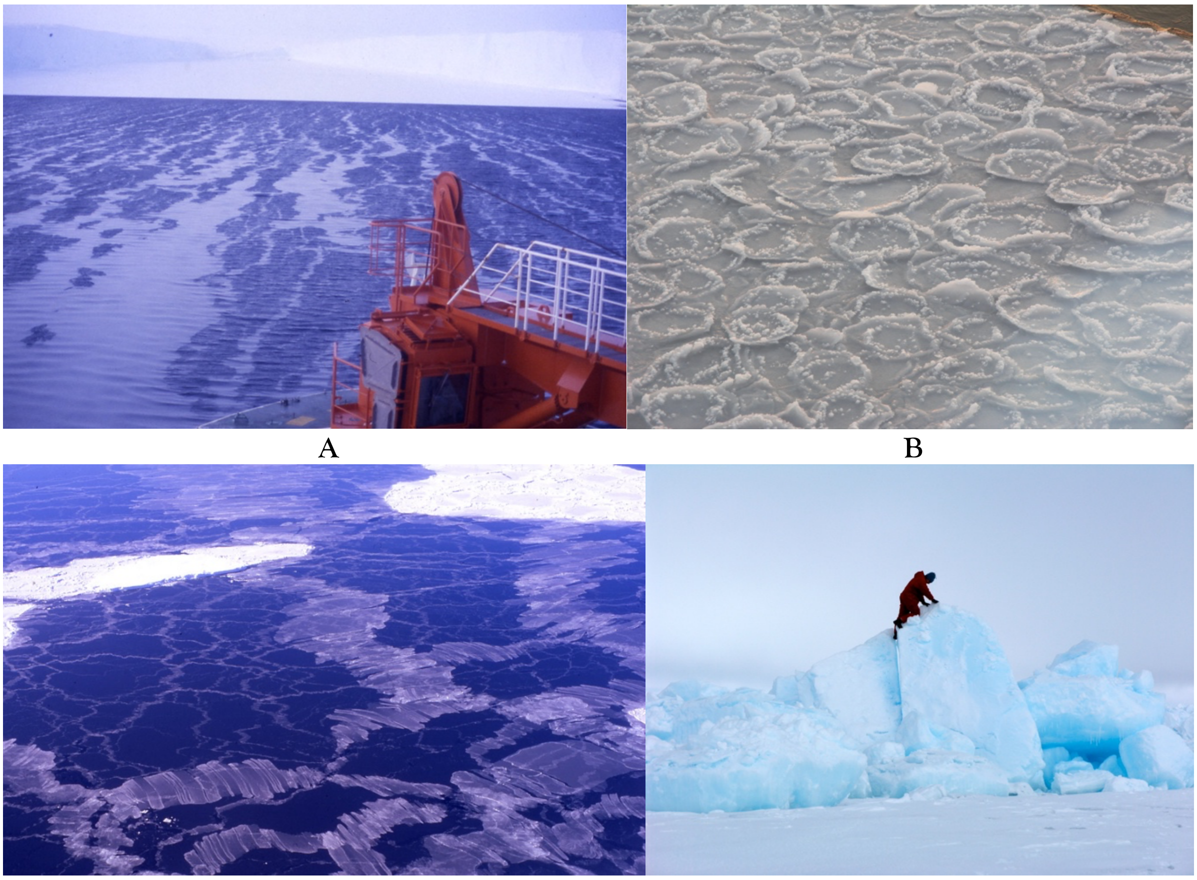
[1]In most regions of the world, seawater contains approximately 34 grammes of dissolved salts per litre. At this amount it is said to have a salinity of 34. If it contained 20 grams of salts it's salinity would be 20 and if it contained 120 grammes of salts the salinity would be 120. Basically, salinity is the term given to the weight (kg) of dissolved salts dissolved in 1 kg of water, and has no units[1]



A B

C D

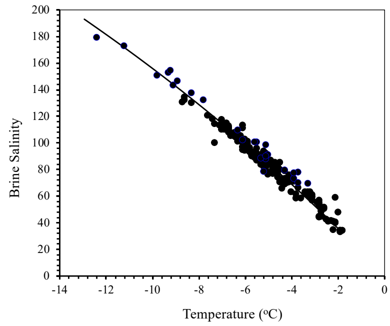
A) Slicks of Grease ice being blown together by the prevailing wind; B) Small "pancakes" (about 30 cm in diameter) being rafted together to form closed ice sheet; C) Sheets of Nilas ice, and where they are rafted on top of each other there is so-called "finger rafting; D) A pressure ridge caused when ice floes collide and the resulting rubble jumbles into ridges on the surface and keels underneath..

3. ***Salt Expulsion into pores and channels***. As the ice moves from the grease ice stage to more substantial forms, the phase transformation continues: as temperatures decrease more ice crystals form, causing the expulsion of more dissolved salts. However, now these salts collect as brines in channels and pores between the crystals. The proportion of channels/pores to ice is dependent on the temperature of the ice. When it is colder there are fewer and smaller channels and when the ice warms there is greater volume of space of larger channels and pores e.g at -10 °C the channels are a few µm in diameter and take up >5% of the space, whereas at -3 °C the channels are mm in size taking up >15% of the space.

In conjunction with the temperature and brine volume shifts, there is a corresponding shift in the salinity of the brines. As the ice gets colder and more dissolved salts are expelled into the brine channels, the salinity of the brines goes up. If the ice warms & ice crystals melt the concentration of salts in the brines is diluted with a reduction in brine salinity e.g. at -6 °C the brine salinity is 100, at -10 °C it is 145 and at -21 °C it is 216.

4. ***Temperature and salinity gradients in ice floes.*** It should be noted that the temperature of an ice floe is not constant and ranges between the temperature at the surface in contact with air and the bottom of the floe in contact with underlying seawater, which is around the freezing point. So, if the temperature of at the surface is -10 °C and the bottom of the floe at -2 °C there

is an 8 °C temperature difference, and hence gradient, which imposes a corresponding gradient of brine channel volume & size and well as brine salinity. This gradient will of course vary, mainly depending on the ambient air temperature, and such variations can be over short periods of time i.e. the low temperature and salinity conditions are changing rapidly even within a single ice floe.



Left: a brine channel viewed under the microscope. The golden brown structures are ice diatoms living within the brine that fills the channel (image curtesy of Christopher Krembs). Right: graph illustrating the relationship between the salinity of sea-ice brines and freezing temperatures. These samples were taken from ice floes in the Weddell Sea in the Southern Ocean during late winter-early spring when the ice temperatures were relatively warm. Temperatures of ice in mid-winter will routinely reach temperatures below -20 °C.

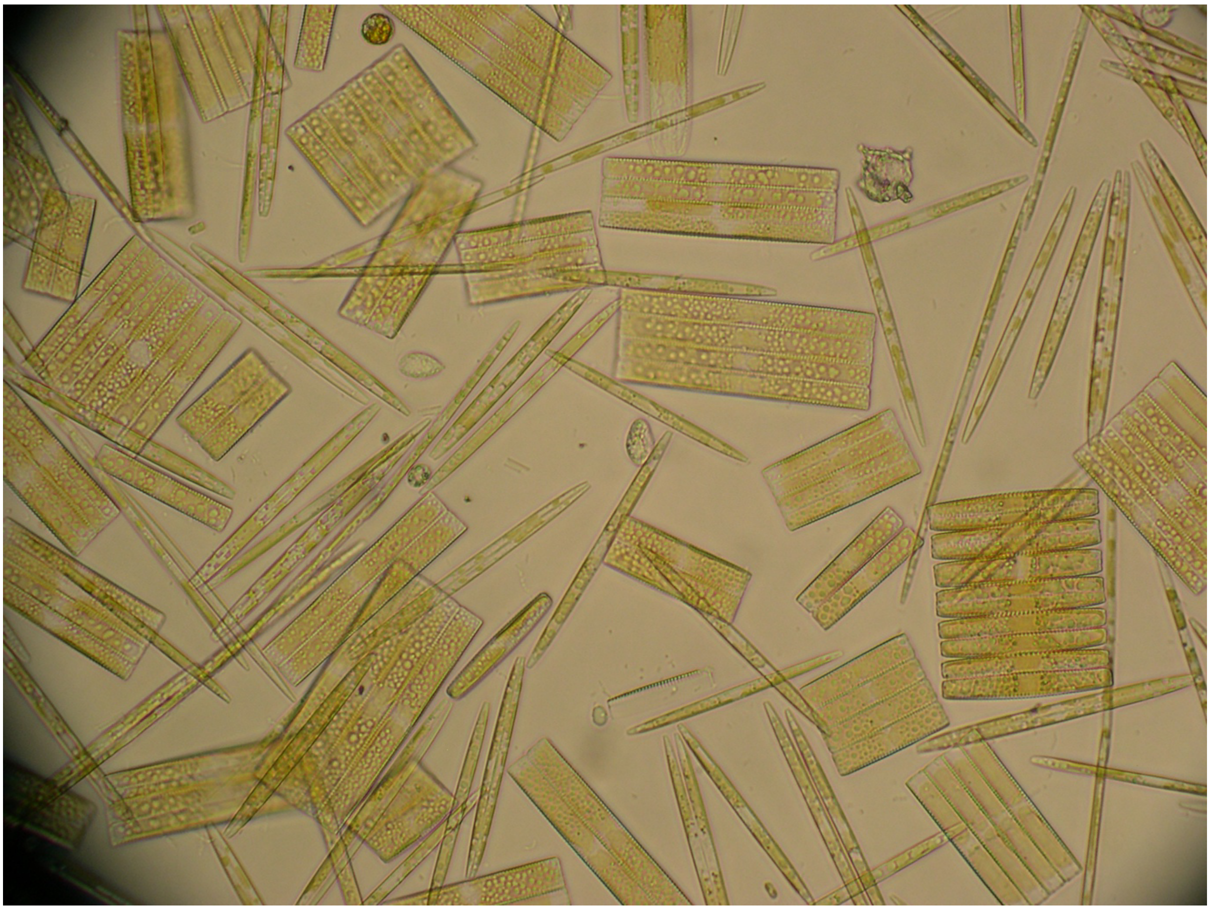
5. ***Ice formation traps floating organisms.*** Organisms of the plankton (viruses, bacteria, microalgae, small zooplankton), those that by definition cannot swim away, get caught up, effectively harvested by the ice crystals as they coalesce into the viscous initial stages of ice. These organisms thereby undergo a complete transformation in the physical medium in which they live:

Liquid with no barriers and exchange → confined liquids in brine channels with limed space and exchange
Liquid of uniform salinity → brines of changeable salinities
Non-freezing temperatures → variable range of freezing temperature.

Transformations on such scales are rare for open ocean dwellers, especially the microorganisms. Massive water masses are highly effective buffers to physico-chemical variations. The current estimated annual production, consolidation and subsequent melt of 30,000 km^3 of sea ice on earth (17,000 km^3 in the Arctic & 13,000 million km^3 in the Southern Ocean) is surely one of the biggest annual biome-shifts on Earth. For comparison the volume of the Baltic Sea is 20,900 km^3. The rapidity with which it takes place could be akin to speed we associate with transformational phenomena such as wild-fires.

6. ***Life in the ice.*** Despite the severe change to living conditions, there are many constituents of the plankton that survive the phase shift and in fact thrive in the new habitat. Assemblages of these can reach such densities that they characteristically stain the ice, often a coffee-colored brown. This results from the pigments contained within a typically dominating constituent of the ice flora, the diatoms. Diatoms are microalgae typical of the plankton (both marine and freshwater), but also importantly found in biofilms and epiphytes on all sorts of surfaces. There is a lot of microbial activity in sea-ice because there is:

a. Lots of sun for photosynthesis. Diatoms are photosynthetic algae and thrive because in the ice they are being constrained in a well-illuminated zone at the oceans surface. This compares to their open ocean existence, in which they and other plankton are routinely mixed throughout the surface layer of the oceans, which can be several hundred meters deep. This means that even if there is a lot of incident light at the ocean surface, they may spend considerable time at depths where light does not penetrate, or penetrates weakly. Of course, the ice, especially if covered by snow, is an effective barrier to light, but in general the photosynthesizing ice algae are in a much higher light regime than under normal planktic conditions.



Diatoms from Antarctic sea-ice under the microscope at x100 magnification (Image curtesy of Jacqueline Stefels).

b. Lots of inorganic nutrients. Light is not the only requirement for growth and an ample supply of inorganic nutrients are also essential. All the key major and trace elements found in seawater are of course proportionally concentrated in the brine formation processes as ice forms. So, they are there in concentrations much higher than in normal seawater.

c. Lots of recycling of organic matter. Marine bacteria also thrive in the ice and contribute to the nutrient supply by breaking down organic matter produced from dead organisms and/or organic matter excreted by living organisms. This "remineralization" of organic matter by bacteria is key to the resupply of nutrients in the open water, but is more enhanced within the ice. This is because the standing stocks of organisms are so much higher, producing significantly greater concentrations of organic matter. Additionally, within the confines of the brine channels the bacteria are significantly closer to organic matter producers than they would be in the open water. This increases encounter rates significantly.

d. Polymer production. Much of the organic matter measured in sea ice is in the form of gel-like polymers excreted by diatoms and bacteria. These substances are thought to be involved in protecting and/or buffering the microorganisms against low temperature and high salinity stress, as well as deterring some grazers from feeding on the microbes producing them. Some species of diatom have also been shown to release ice nucleating proteins that alter the freezing properties of their surrounding water/brine.

Growth of diatom-rich microbial assemblages in ice can result in such concentrations that the ice is turned brown from the pigments contained within the diatoms. Left: overturned ice floes revealing the brown undersides; Right: the bottom of an ice core showing greater detail of the bottom brown layer. The ice core is 10 cm in diameter.

e. Survival after entrapment. Not all plankton that are swept up by the curtain of ice crystals rising through the surface waters during initial ice formation survive. Clearly many are too large to fit into the µm-sized brine channels, and others do not have the physiological capability to survive the temperature and salinity stresses. Those organisms that do survive incorporation into ice, by definition have to be able to withstand wide-ranging salinities and temperatures far in excess of anything they would experience in the open water. Not only this, but they have to be able to respond to rapid changes in these key parameters. The swift regulation of production of osmoprotectants - cellular ions and compatible solutes - that provide protection against salinity stress (and other forms of stress) are therefore key to survival. Some solutes, such as the amino acid proline and dimethylsufoniopropionate (DMSP for short), have both a role in adjusting osmotic balance within cells as well as combating the effects of freezing.

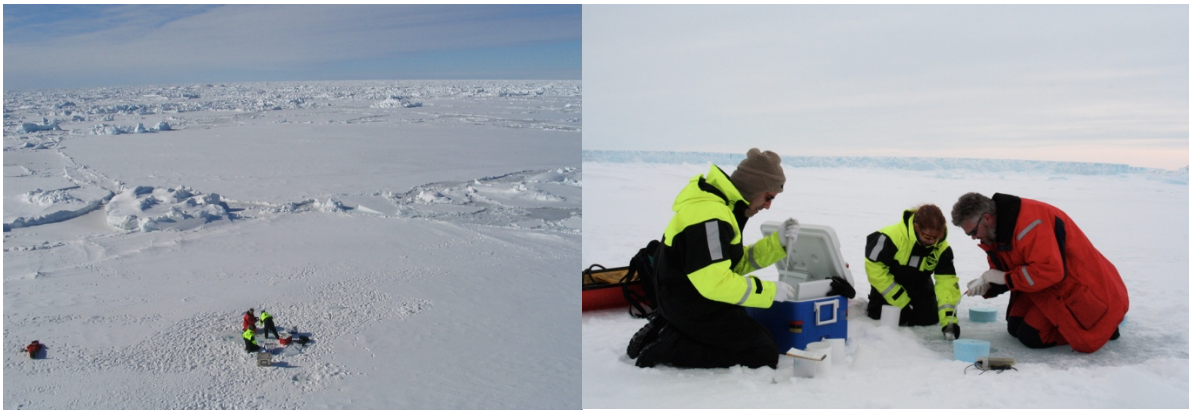
7. ***Sea-ice microbes as food and their integration into the marine food web.*** The assemblages of algae (diatoms are not the only ones) and bacteria are in turn food for many grazing protists including ciliates, heterotrophic flagellates and foraminifers. These have all been recorded in large numbers in the ice, especially in biologically-rich zones in the ice. Additionally non-microscopic (visible to the naked eye) grazers, such as small copepod species, turbellarian and nematode worms, if small enough to fit into the brine system, use the ice as rich feeding grounds.

At the edges of ice floes, which are at the freezing/melting point of seawater, the ice is more porous than inner ice that is normally colder and less porous. These edge regions attract even larger species of grazing organisms to feed on the algal/bacteria-rich resources. These include nudibranchs, large copepods, amphipods, krill and even some fish. These in turn are a direct link from the microbial foodweb in the ice to the much wider foodweb in the open water. A good example is the Antarctic krill which swarm in the Southern oceans in huge numbers (akin to locusts in terrestrial systems) and are a key food for squid, seals, penguins and baleen whales. Having the sea ice food resource in early spring is key for some krill populations to grow at a time of the year when food in the open water is scarce. So a lack of sea ice could impact krill numbers and in turn the numbers of the larger species that depend on krill.

Fig.6. Bottom of an ice core where the krill that had been feeding at the underside of the ice floe are visible. Although not as pronounced as Fig. 5, the staining of the ice by brown diatoms, on which the krill were feeding, as still visible. The ice core is 10 cm in diameter and the krill are 1-2 cm in length.

Not only do the microbial assemblages in the ice feed grazers close to the ice, but when ice melts in spring/summer this food resource is deposited into the surrounding waters. Some is consumed directly by grazers and some goes on to seed ice edge blooms of phytoplankton that become rich feeding grounds for zooplankton and, in turn, those organisms feeding on them.

Much of the microbial biomass released from melting ice sinks rapidly to the sea floor (the benthos) where it is consumed by benthic filter-feeding organisms. So, microbial ice communities are key to the productivity of both pelagic and benthic animals in seasonally ice-covered oceans and seas. The seasonality, or phenology, of food-web productivity in these waters is for these reasons strongly associated with the microbiology in the ice. Changes in the latter due to climate change will have profound implications for the former.



Team of scientists studying the secrets of an Antarctic ice floe, with a closer view of their work, here measuring the oxygen concentration of the sea-ice brines. (Images curtesy of Gerhard S. Dieckmann).

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture**. The microbial assemblages in and around sea ice are key to the food webs in arctic and Southern oceans. They are therefore vital to the sustainable exploitation of food resources from these regions.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages**. In particular for Arctic indigenous coastal communities, a predictable and healthy marine food web is essential.
- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.** There is considerable industry surrounding marine food webs in polar regions, and so ice associated organisms play a big role in sustaining this. Both Arctic and Antarctic polar regions have large tourism industries associated with charismatic mega-fauna, for which the microbial food web is ultimately vital. Many Arctic indigenous cultures and economies are intrinsically linked to seasonal sea ice progressions and resulting availability of marine resources.
- **Goal 12. Ensure sustainable consumption and production patterns.** See Goals 2 & 3 above.
- **Goal 13. Take urgent action to combat climate change and its impacts.** The microbial assemblages of ice and associated waters are fundamental for the production and consumption of greenhouse gases. Changes in the seasonal dynamics of microbial food webs in the Arctic and Antarctic will impact of the seasonal dynamics of greenhouse gases in those regions.
- **Goal 14. Conserve and sustainably use the ocean, seas and marine resources for sustainable development.** The Arctic Ocean is 1.4% and the Southern Ocean 5.4% of the total ocean volume on Earth. The key role of microbial assemblages for food webs in both are essential for the sustainable use of marine living resources.

Potential Implications for Decisions

1. ***Individual***

a. Global warming is the biggest challenge for life in ice. Identify all your activities, especially the food you eat, that contribute directly and indirectly to greenhouse gas production, and consider the personal decisions you could make that might reduce your contribution.

b. Polar environments are very fragile and tourism places considerable strain on them. Would you like to experience the excitement of unique polar environments? If so, how would you like to do this while minimizing your footprint?

2. ***Community policies***

a. What policies can our community develop and implement to reduce its carbon footprint?

b. What role can education in our community play in this?

3. ***National policies***

a. Relating to greenhouse gas emissions
b. Relating to environmental pollution, especially air pollution
c. Relating to international treaties to protect polar environments
d. Relating to protection of marine systems

Pupil Participation

1. Class discussion topics

a. The microbes in ice and water are key to determining the ultimate numbers of polar bears, seals, birds and whales in polar regions.

b. How will changing ice conditions due to climate change impact on the timing of seasonal marine food webs in seasonally ice-covered oceans and seas?

c. What are the consequences of climate-induced changes to marine foodwebs for indigenous people living in Arctic coastal communities.

2. Pupil stakeholder awareness

a. Everyone contributes to a greater or lesser extent to greenhouse gas emissions. Energy consumption is one significant parameter. How might you reduce the amount of energy your activities consume, e.g. showering, cooking, etc?

3. Exercise

Food chains in Antarctic regions can be relatively short, e.g. algae and microbial assemblages are eaten by krill which in turn are the main food source for (a) Humpback Whales, (b) Crabeater Seals, (c) Adelie Penguins, and (d) Emperor Penguins.

Search to find the average weight of adults of these 4 krill-consuming species and then work backwards to calculate the weight of krill they would have to eat to reach that adult weight, and then in turn what the weight of algae/microbes the krill would have to eat.

N.B. In marine systems the efficiency of energy transfer between stages in a food chain are between 10 and 30%. That means that for every kilogram of one stage it will produce only about 10 to 30 grammes of the subsequent stage

The Evidence Base, Further Reading and Teaching Aids

Papers/ Books

Mock, T. and D.N. Thomas (2005). Recent advances in sea-ice microbiology. Environmental Microbiology, 7, 605-619.

Steiner, N.S. et al. (2021) Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene, 9: https://doi.org/10.1525/elementa.2021.00007
Thomas, D.N. and G.S. Dieckmann (2002) Antarctic sea ice – A habitat for extremophiles. Science, 295, 641-644
Thomas, D.N. (ed) (2017) Sea ice 3rd Edition. Wiley-Blackwell, Oxford.
Thomas, D.N. and D.G. Bowers (2021) Introducing Oceanography, 2nd Edition. Dunedin Academic Press. Edinburgh.

Websites

National Snow & Ice Data Center for daily Sea ice news & analyses. Website: https://nsidc.org/
NOAA for their Annual Arctic report card. Website: https://www.arctic.noaa.gov/Report-card
Arctic Monitoring & Assessment Programme (AMAP) for key Arctic reports. Website: https://www.amap.no/

Reports

IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Download from https://www.ipcc.ch/srocc/
IPCC Sixth Assessment Report: Impacts, Adaptation and Vulnerability. Download from https://www.ipcc.ch/report/ar6/wg2/
ICCI State of the Cryosphere 2021- A Needed decade of urgent action. Download from https://iccinet.org/statecryo21/
Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy Makers. Download from https://www.amap.no/documents/doc/arctic-climate-change-update-2021-key-trends-and-impacts.-summary-for-policy-makers/3508
The United Nations Decade of Ocean Science for Sustainable Development runs from 2021 to 2030 (https://www.oceandecade.org/). Key action plans have been produced for the Arctic and Southern Ocean and these comprehensively outline key issues for both regions:
a) Arctic Action Plan (2021-2030). Download from https://www.oceandecade.dk/decade-actions/arctic-action-plan
b) Southern Ocean Action Plan (2021-2030). Download from https://www.sodecade.org/action-plan/southern-ocean-action-plan/

Glossary

Algae: aquatic organisms varying in size from single-celled organisms (microalgae) through to giant seaweeds (Macroalgae). They are not plants, but do photosynthesize. Unlike plants they do not have roots, vascular systems and do not have flowers.
Benthic: Term given to organisms living in or on the sea/ocean floor (the benthos)
Biofilms: Assemblage of microorganisms adhering to a solid surface, often within a mucilage layer.
Brine: Water with salt in it, although in sea ice it is used to describe waters with more salt in it than normal seawater.
Diatoms: Microalgae covered in hard silicate frustule.
Epiphytes: An organism growing on the surfaces of plants or algae
Nutrients: Elements and compounds essential for the growth of an organism. The are many and varied but key are carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur

Osmoprotectant: Ions or organic molecules whose concentrations can be varied within a cell in response to osmotic change outside of the cell.
Pack ice: Sea-ice floes that are moved on the surface of the ocean by wind, tides and ocean currents.
Pelagic: This is the open sea/ocean and includes the whole water column. Pelagic organisms are those that live in the open waters. Compare with benthic above.
Photosynthesis: The process by which plants, algae and some bacteria use sunlight, carbon dioxide and water to form sugars for growth
Plankton: Organisms that drift freely with the prevailing winds, currents in the seas, oceans and lakes.
Remineralization: The conversion of organic matter into constituent elements that can be used as nutrients. Bacteria and fungi are the major organisms involved in the breakdown of organic matter and the release of key elements such as nitrogen and phosphorus.
Zooplankton: Animals living in the plankton (see above)