Life in the Cold

Daddy – if I spend too long outside in the snow, I'll freeze to death. How can anything survive and live in very cold environments?

The Antarctic region is the coldest part of planet Earth. Even in mid-summer, daytime temperatures around the coast of the Antarctic continent rarely get above freezing point, and the central ice-cap (which covers most of the continental land-mass) is very much colder. Despite the freezing conditions, the coastal ice-free zones (shown above) are very rich in living microbes, mosses and lichens.

Don Cowan

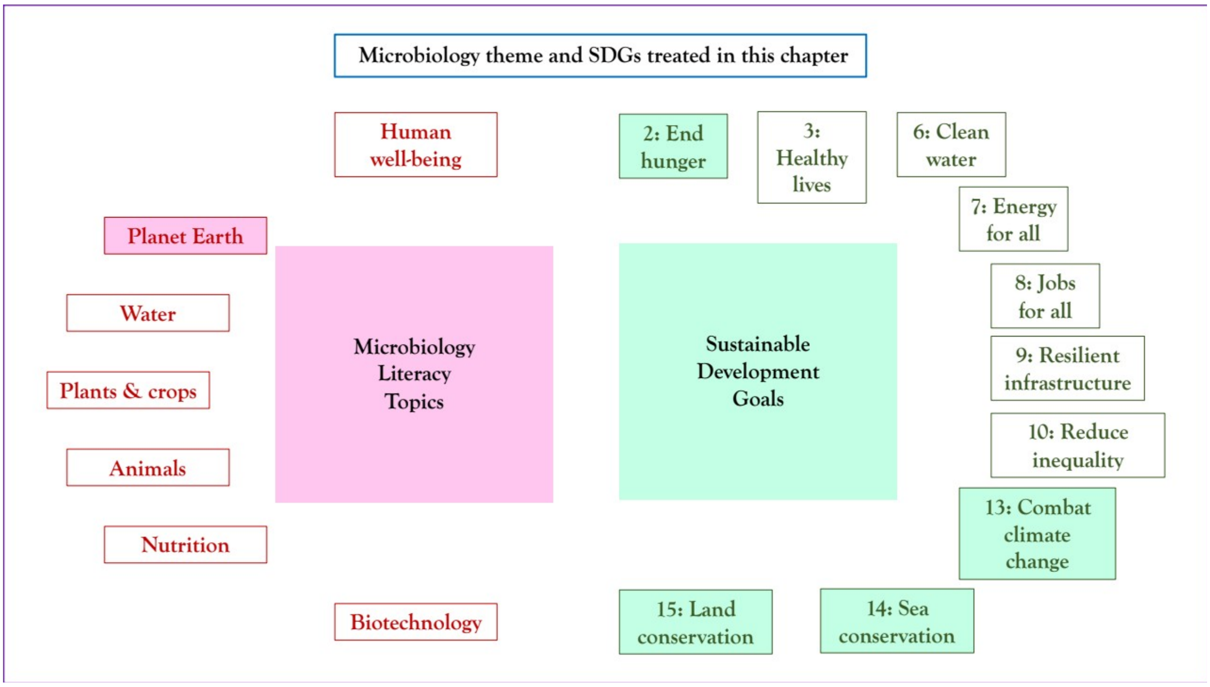
Centre for Microbial Ecology and Genomics, Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Pretoria, South Africa

Life in the Cold

Storyline

Cold is a part of life on Earth, and has been since life first developed on this planet some 3.4 billion years ago. The world's poles, high mountains and deep oceans all provide habitats for different biological communities, including humans, marine mammals, fish and crustaceans, plants and microorganisms. The apparent severity of very cold environments is something of an anthropogenic viewpoint: a temperature that might seem very cold to us as warm-blooded humans is 'normal' to a cold-loving microorganism. In consequence, it has been found that even the coldest parts of the world harbour large and complex populations of microorganisms, and these remote regions and their inhabitants are both relevant to and important for the sustainable Development Goals.

The Microbiology and Societal Context



The microbiology: cold habitats; inhabitants of cold habitats; adaptations to survive cold; the environmental and economic relevance of cold-loving organisms; relevance to global issues and the SDGs.

Life in the cold: The Microbiology

1. ***No-one likes to be cold! And yet…*** Humans are warm-blooded (body temperature typically around 37°C) and have a rather narrow operating temperature range. If your core body temperature goes much above 39°C (fever) or below 35°C (hypothermia), you are in trouble. Yet, despite these severe limits, humans have been living in the extremely cold regions of the world for millennia: the Inuit peoples of the high Arctic are the best examples. We survive the cold by internal heat generation, external heating, insulation and protection.

But microbes have none of these abilities. They are exposed to the temperatures of the environment in which they live, wherever they are, and must just deal with it! ! Nevertheless, some microbes thrive in cold environments and those that do provide important ecosystem services and processes and products for biotechnology.

2. ***Cold-adapted microorganisms.*** Scientists love to classify things! It makes them feel safe and happy. So cold-loving organisms were classified into defined groups decades ago. Firstly, the term psychrophiles was coined to describe all cold-loving organisms, sub-classified into psychrotolerant organisms (those that tolerate cold but prefer to be warmer) and extreme psychrophiles (those that need to live at low temperatures, and do not survive at temperatures above about 30°C).

3. ***Cold environments for microbes.*** The obvious cold environments on Earth are the Arctic and the Antarctic. In the north (Arctic), an ice-covered ocean is surrounded by the cold coastal lands of northern Russia, Canada, Norway and Greenland, and by a few chilly islands such as Iceland. In the south, the Antarctic continent (roughly twice the size of Australia) is almost completely covered by thousands of meters of permanent ice.

Mountains and high altitude plateaus are also cold habitats. The major alpine regions of the world – such as the European Alps, the North American Rockies and the South American Andes – represent about 27% of Earth's terrestrial surface.

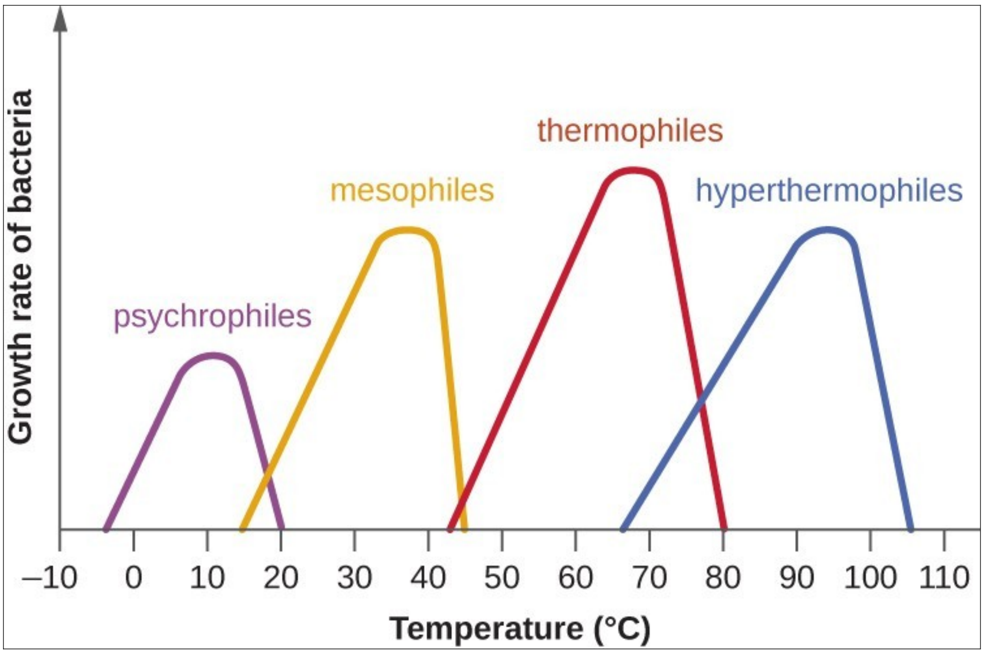
The polar oceans are cold, as are the very deep (abyssal) oceans around the world. Deep ocean waters are typically around 4°C. Given that about 70% of Earth's surface is covered by water, oceans represent a major portion of the world's cold habitats.

Important, but easily forgotten, are the man-made cold habitats, in the form of domestic and industrial refrigerators (around 4°C) and freezers (around -18°C). These man-made cold habitats provide a stable environment for psychrophilic microbes, along with a plentiful supply of nutrients and growth substrates (foodstuffs, organic materials, etc.).

Antarctica is the coldest place on Earth. The South Pole has a mean annual temperature of -46°C, with upper and lower mean temperatures of -25°C and -61°C, respectively. The coldest temperature ever recorded on Earth was -89.2°C, at the Russian Vostok Station high on the Antarctic ice-cap. This temperature is lower than the freezing point of carbon dioxide (-78°C). Despite these extraordinarily cold conditions, microorganisms exist in any suitable habitat across the Antarctic continent. Viable microbes can be isolated from thousand year-old ice cores from the Antarctic ice-cap; these microbes are probably dormant but they are still alive.

4. ***The effects of cold on microorganisms.*** Temperature has dramatic effects on biological processes. Reaction rates (for enzymic reactions for example), conformational changes in proteins and the fluidity of cell membranes are all reduced with lower temperatures.

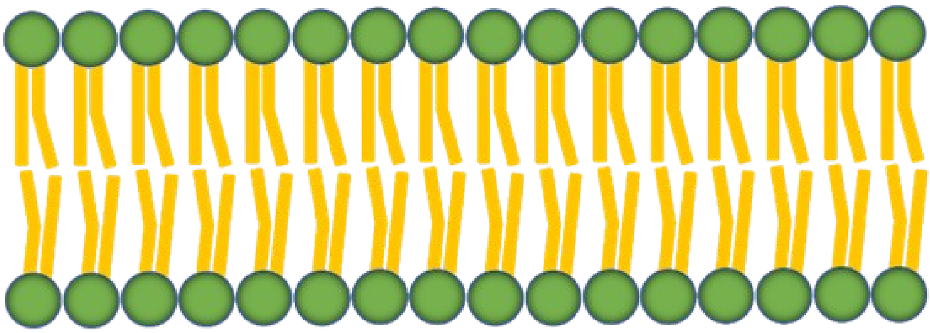
The rule of thumb is that reaction rates double with every 10ºC rise in temperature, and *vice versa* for lowering temperatures. These rules apply to microbes in their natural environments, suggesting that psychrophilic microbes should metabolize and grow much more slowly than microbes in warmer temperate environments. While psychrophilic microbes exhibit a range of structural and biochemical adaptations to compensate for their low temperature lifestyle, their growth rates are typically slow.



Growth rates of different groups of microbes: from cold-loving (psychrophiles) to extreme heat-loving (hyperthermophiles.

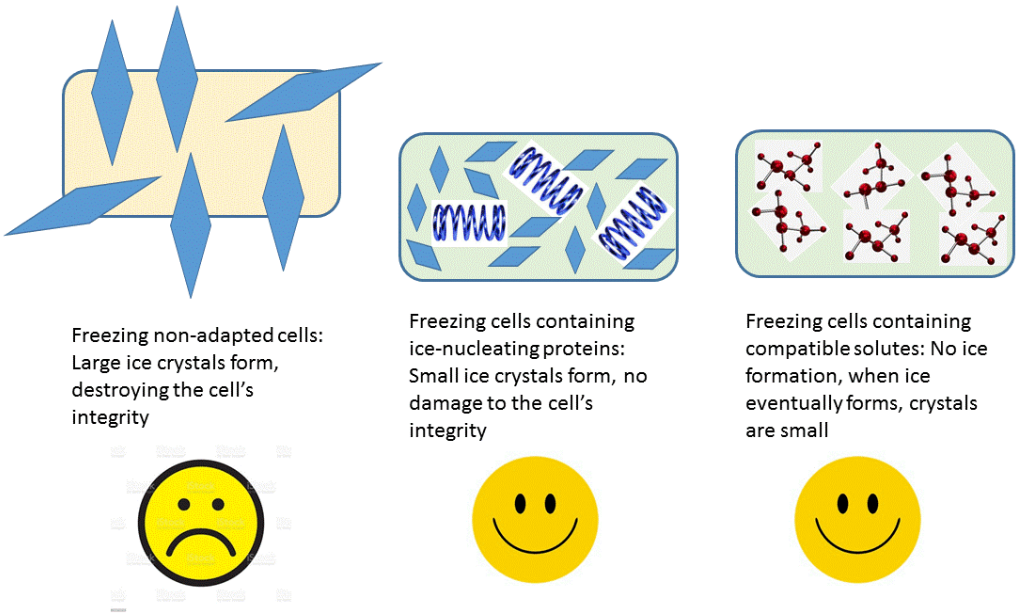
5. Adaptations to survive cold. Psychrophilic microbes have evolved a raft of molecular and structural adaptation to cope with the negative effects of cold on the kinetics and thermodynamics of cellular processes. For example, the reduction on protein flexibility caused by lower temperatures is addressed by changes in protein amino acid content, designed to reduce weak intramolecular interactions (such as the number of salt-bridges and H-bonds) and make the protein structures more flexible.

The lipid bilayer structures of cell membranes, where membrane fluidity is critical for cellular survival, become less fluid as temperatures drop. In psychrophilic organisms, membrane constituents are adapted to increase fluidity at low temperatures; typically by shortening the length of aliphatic tail structures, and adding methyl side-chains so that the alignment of fatty acyl tails is disrupted.



Structure of a lipid bilayer, with glyceryl heads (green) and fatty acyl tails (orange).

Cellular freezing is very damaging in most organisms: the formation of large ice crystals inside cells fractures the cell wall. Frozen tissues (such as frostbite in humans) results in massive cellular damage, and often results in the loss of the frozen organ, such as a finger or toe. Psychrophilic microbes have evolved various mechanisms to avoid this damage. Ice-nucleating proteins actually stimulate ice crystal formation, but with the formation of very small ice crystals that do not damage cell walls. An alternative mechanism is the rapid synthesis of compatible solutes (sugars, sugar alcohols and other small highly soluble organic molecules) inside the cells. High concentrations of intracellular compatible solutes provide protection to cell constituents and depress the freezing point of water. Similarly, the synthesis of special anti-freeze proteins inside the cell also prevents freezing.



*6. **The global importance of cold-microbes.*** Microbes play vitally important roles on a global scale.

a. Carbon sequestration. Their capacity to absorb carbon dioxide, particularly in the world's oceans, is a major contribution to the world's carbon sequestration budget.

b. Plant productivity. Microbes in soils play a very important role in the growth and productivity of plant species, and therefore contribute substantially to world's agriculture and the food supply sustainability. The best-known example of this vital contribution is the presence of nitrogen-fixing bacteria in the root nodules of leguminous plants, where these microbes provide much of the N needed for optimal plant growth.

*7. **Cold microbes and climate change.*** Psychrophilic microorganisms have achieved some notoriety over the past decade, largely because of their capacity to contribute to global warming. Two examples show just how important microbes may be in future climate change scenarios.

a. The Arctic tundra permafrost contains enormous stocks of fixed organic carbon. In a warming world, melting permafrost activates methane-producing microbes that have lain dormant for centuries or millennia. Methane production from melted permafrost –

still a cold environment populated by microbes - is likely to make a major contribution to global greenhouse gas production.

b. Secondly, snow algae (photosynthetic microbes, with green or pink pigmentation) live on the surface of snow-fields in places such as Greenland. The coloured cells adsorb heat from the sun, and dramatically accelerate the rate of surface snow-melt. A warming climate favours the growth of these microbes and accelerates the rate of glacial melting; the melting of terrestrial ice and snow contributes to rising sea levels. This process is already an issue in the Arctic and ice mass loss from the Greenland ice cap is increasing rapidly.

8. ***The economic relevance of cold-active microorganisms.*** Psychrophilic microbes have both good and bad impacts on economically important processes and products. For example, the spoilage of food by psychrophilic microbes during refrigerated storage is a major concern. Conversely, psychrophilic bacteria play a very important role in the bioremediation of oil spills (see references to the 10 million US gallon Exxon Valdez oil spill in Alaska in 1989). Similarly, cold-active enzymes derived from psychrophilic microorganisms have become valuable additives to domestic washing powders, as trends in domestic washing practices have moved towards lower temperatures.

Relevance for Sustainable Development Goals and Grand Challenges

Cold habitats and their inhabitants are relevant to many of the 17 SDGs, on many levels. The SDGs which are of greatest relevance include:

SDG2: Zero Hunger
SDG13: Climate action
SDG14: Life below water
SDG15: Life on land

The cold regions of the world, both terrestrial and marine, are either colonised by human populations (SDG15: for example, the Inuit peoples of the high Arctic) or provide important sources of food (SDG2, SDG14: for example, the fisheries of the southern oceans). These regions can contribute to climate change and its consequences (SDG13: for example, methane release from warming permafrost, or sea-level rise from glacial melt). Cold habitats and their inhabitants can also help ameliorate the effects of global warming (SDG13); the photosynthetic phytoplankton of the southern oceans play a very important role in fixing and sequestering atmospheric carbon dioxide.

Potential Implications for decisions

1. ***Individual.***

The cold regions of the world are very large, and many are subject to multi-national interests. It might seem that little impact can accrue from the actions of any individual. Nevertheless, most of the world's governments, which individually or collectively can establish legislation for the conservation of sensitive cold habitats, are subject to the political will of their electorates. The multi-party structures of many of the world's democracies offer the potential for individual voters to choose the party which has the strongest conservation objectives within its manifesto.

2. ***National and International policies.***

The cold terrestrial environments of the world (Arctic, Antarctic, Montane) are particularly susceptible to human impact, whether direct (such as tourism and recreation, or mining) or indirect (via anthropogenic impacts on climate change). The former can only be addressed by robust conservation legislation at the national level, designed to limit or control such activities in sensitive cold environments. The same applies to cold marine habitats: shallow coastal zones tend to be the breeding grounds for the economically important pelagic fish species, and their conservation requires either strong protective legislation at a national level, or global consensus (for the coastal regions of the Antarctic continent, where no national ownership rights exist).

Pupil Participation

1. ***Class discussion on cold environments and organisms that inhabit them***
   a. Focus on animals and plants in cold habitats

2. ***Pupil stakeholder awareness***
   a. How does extreme cold affect organisms? How is this relevant to food storage?
   b. What could be done to protect cold-sensitive organisms (e.g., plants) from the effects of cold (in agriculture, for example)? Hint: plant breeding, genetic engineering.
   c. What is going to happen to obligate psychrophiles (those organisms that require a cold environment to live) with the ongoing warming effects of global climate change?

3. ***Exercises***
   a. Looking at the SDGs, decide which are most relevant to life in the cold? What needs to be done (within the context of the SDGs) to protect and conserve cold environments in the 'natural' world.
   b. How will global warming impact cold environments and, subsequently, human populations. Hint: glaciers and ice-caps; cold ocean currents

The Evidence Base, Further reading and Teaching Aids

Life in the Cold: An Introduction to Winter Ecology, Fourth edition, Peter J. Marchand, University Press of New England
www.coolgeography.co.uk/gcsen/GCSE_LW_Cold_Characteristics.php
worldoceanreview.com/en/wor-6/polar-flora-and-fauna/living-in-the-cold
Life in the Freezer. David Attenborough, BBC Earth series.

Glossary

Abyssal: The ocean zone below 3,000 metres depth, which is perpetually dark. The abyssal zone covers 83% of the total area of the world's ocean and 60% of Earth's surface.
Amino acid: The building blocks of proteins
Anthropogenic: Relating to or influenced by humans
Carbon sequestration: A process by which carbon dioxide is taken from the atmosphere and converted into a stable solid form (such as plant biomass)

Cell membrane A twin-layered structure surrounding living cells: most commonly two layers of lipid (fat) molecules. The cell membrane, which controls the passage of water, ions and organic molecules in and out of the cell, is vitally important to the cell.

Compatible solute: A small water-soluble molecule which can accumulate to high concentrations inside cells, protecting large macromolecules and preventing ice formation.

Conformational 'Shape'; a term typically applied to proteins to describe it shape and shape-changes

Enzymic [Adjective] Reactions carried out by enzymes

H-bond: Hydrogen-bond: a weak (non-covalent) electrostatic bond between a H atom and an electronegative atom such as O.

Hypothermia: A clinical state where the core body temperature drops below 35°C.

Ice core: A frozen 'core' sample removed from glacial ice by drilling

Ice-nucleating: Small particles which have the capacity to trigger ice formation in a freezing liquid, with the formation of multiple very small ice crystals

Inuit: People of the high Arctic, formerly known as Eskimos

Kinetics: The rate or speed of a process

Metabolize(ism): A term describing the biochemical processing of organic molecules inside a cell

Methane: CH_4: A greenhouse gas generated both biologically (by highly specialized methane-producing microorganisms) or by 'abiotic' geological processes.

Nitrogen-fixing bacteria: Bacterial (termed diazotrophs) that are capable of converting atmospheric nitrogen gas (N_2) to organic nitrogen-containing molecules such as amino acids

Permafrost: A deep soil horizon which remains frozen all year round

Photosynthetic: Capable of using sunlight to generate energy, involving pigments such as chlorophyll.

Psychrophil(e)/(ic): 'Cold-loving'; a term used to describe microorganisms that prefer to live in cold environments

Psychrotolerant: 'Cold-tolerating' organism. Capable of surviving low temperatures, but preferring to live at higher temperatures.

Root nodules: Specialized structures on the roots of leguminous plants that harbour N-fixing bacteria such as *Rhizobium* species.

Salt bridge: A weak (non-covalent) electrostatic bond between two charged amino acid side chains (such as a carboxylate group (negative) and an amino group (positive).

Thermodynamics: A concept in physics that deals with heat, work and temperature, and their relation to energy, entropy and the physical properties of matter.