Microbial ecosystems of Antarctica

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Cover: Scanning electron micrograph of a cyanobacterial mat from Fryxell Stream, southern Victoria Land

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Introduction

Extreme cold has shaped the antarctic environment and the microbial communities that live within it. Even throughout summer, air temperatures at the margins of the continent and in the maritime zone lie between −10 and +5 °C. The dramatic and discontinuous change in the physical properties of water over this range, in particular at its freezing point (Fig. 1.1), has a far-reaching impact on the chemical and physical characteristics of all potential habitats throughout the region. These environmental effects restrict the types of organisms that can be supported, and severely limit the timing and intensity of biological processes.

The freezing and melt cycle exerts the dominant influence on antarctic life forms, although not always directly. Persistent snow and ice are a feature of many antarctic environments (most obviously the continental ice sheet, and the vast expanse of sea ice that encircles the continent each year), even during the period of maximum biological activity. Freezing and melting dictate the areal extent of these environments that in turn modify other properties of the region – for example the distribution of water masses in the Southern Ocean (see Chapters 4, 5) and the regional variations in climate (Appendix 1). For the organisms which live within snow and glacier ice (see Chapter 2), the various forms of sea ice (see Chapter 3), or the permafrost-influenced soils (see Chapter 8), growth and reproduction are totally dependent upon the minute pockets of liquid water, and during freezing and melting these are subject to major fluctuations in volume, osmolarity, pH and temperature. Ice formation can physically disrupt environments (e.g. parts of the marine benthos subject to ice-scouring or anchor ice effects (see Chapter 6)) or cause large-scale changes in the salinity and gas content of the remaining water and the amount of light that penetrates down into it (e.g. ice-capped lakes and pools (see Chapter 7)). Rapid shifts backwards and forwards across the freezing point may effectively sterilise certain environments or force the

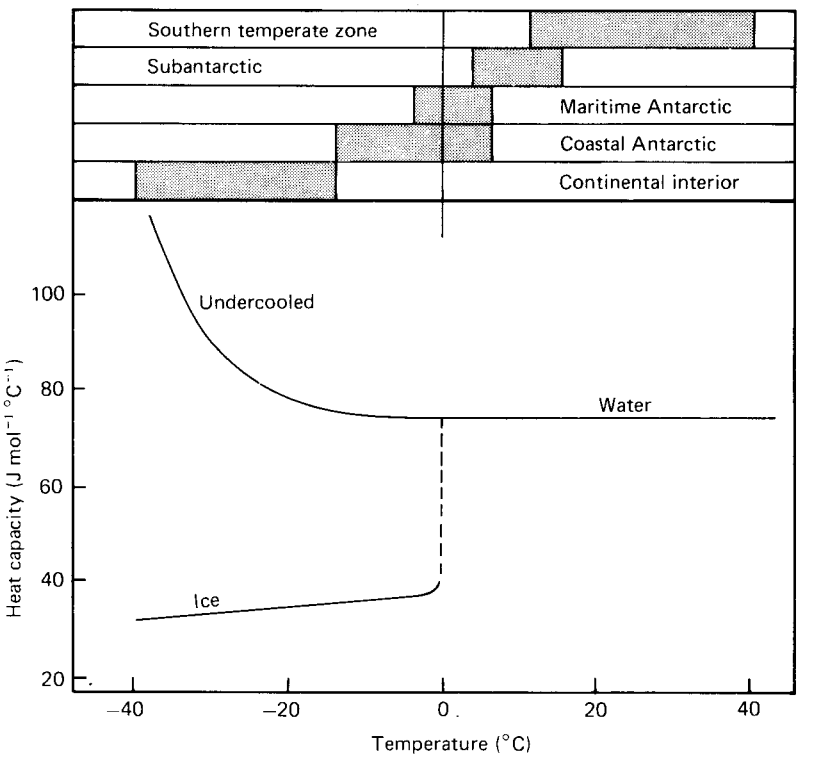

Fig. 1.1. Even in January, the warmest month for biological activity, air temperatures throughout much of Antarctica lie in the range −10 to +5 °C (the shaded bars represent the temperature range for each region, from mean daily minima to mean daily maxima; full data in Appendix 1). The abrupt shift in the properties of H_2O across this range, illustrated here by heat capacity (after Franks, 1985), has a major influence on the distribution and activity of the biota.

micro-organisms into thermally more stable parts of the habitat, e.g. abiotic rock faces and the well developed microbial communities at depth beneath the rock surface (see Chapter 9). Conversely, for certain habitats the formation of an ice cover provides insulating protection from the outside environment, and may allow liquid water to persist despite sub-zero air temperatures.

The subsequent melting process often occurs rapidly. This causes an abrupt improvement in growth conditions that may amplify the effects of the strongly seasonal light regime on primary production and subsequent food chain processes. Most of the Southern Ocean for example, contains sparse concentrations of microalgae (phytoplankton) that have low photosynthetic rates (see Chapter 5). When the sea ice breaks up each year, the

lower salinity meltwater restricts vertical mixing and retains the phytoplankton under improved light conditions for photosynthesis; this is believed to cause a band of intense primary and secondary production that sweeps across the ocean behind the retreating ice pack (see Chapter 4). Ice shelf (see Chapter 2) and meltwater stream (see Chapter 7) ecosystems in Antarctica are fundamentally linked to radiation and temperature, and small shifts in the energy balance at their ice faces may markedly alter the availability of water for aquatic life in these ecosystems. With summer air temperatures typically remaining close to 0 °C in many antarctic habitats, small changes in local climate can completely shift the balance between freezing and melting and thereby dramatically change the chemical and physical environment. As a result many antarctic ecosystems might be expected to show large interannual variations in the timing and duration of conditions favourable for biological processes.

Marked changes also take place in the immediate cellular environment during the freezing and melt cycle. Extracellular ice formation results in severe dehydration, often compounded by osmotic stress; intracellular ice formation generally causes the death of the cell. Antarctic microorganisms, like those in other freezing habitats have a range of adaptive strategies that allow them to avoid or at least minimise these destructive effects (see Chapter 10).

Cold temperatures above freezing may also exert a decisive influence on the activity and species composition of antarctic communities. At a cellular level these effects operate in part through the Arrhenius relationship between chemical reaction rate and temperature. However for many species in Antarctica and elsewhere there are major departures from this simple function, even within the ambient temperature range. Some of these responses to cold operate at the cellular macromolecule level. The extent of hydrogen-bonding of proteins with water molecules is a determinant of their catalytic activity and this surrounding water structure is sensitive to temperature. Similarly, temperature has a major influence on the fluidity of lipid membranes that in turn regulates many cellular functions (see Chapter 10). These biochemical and biophysical stresses may be exacerbated by further chemical interactions in habitats where freezing has generated high solute concentrations and unusual pH regimes.

Low temperatures may have a differential effect on select components of the community. In microbial consortia of phototrophs and heterotrophs, the markedly different responses to temperature by each functional component (e.g. fungal respiration versus net photosynthesis by the algae in the microscopic lichens that live within certain rocks (see Chapter 5)) can

further generate pronounced non-linearities in the temperature response curve. These effects of low temperature may strongly interact with other environmental variables including light intensity (e.g. net carbon fixation by the rock microbial communities), daylength (e.g. net photosynthesis in the Southern Ocean) and pH (e.g. methanogenesis in moss tundra soils). They may also influence the usefulness of traditional descriptors of microbial activity – for example chlorophyll *a* does not seem to decompose completely in various cold water environments and may be a misleading guide to phototrophic biomass in communities such as the marine benthos (see Chapter 6) and stream microbial mats (see Chapter 7).

Antarctic microbial communities are fiercely regulated by their extreme environment, but they may also have a reciprocal influence on the physical and chemical properties of their surroundings. For example, the presence of dense growths of diatoms in the sea ice substantially lessens its physical strength (Buinitsky, 1977) and may thereby hasten its decay. The communities within the rocks can accelerate the rate of erosion by exfoliation; these rock-dwelling microbes appear to live in a 'precarious equilibrium' between slow growth and destructive biotic and abiotic weathering (Friedmann & Weed, 1987). Similarly the growth of snow algae and ice mats can markedly alter the albedo of these environments and accelerate the rate of ablation. Dense populations of planktonic microalgae within ice-covered lakes can affect the distribution of heat and encourage relatively fast rates of mixing by penetrative convection (Matthews & Heaney, 1987).

Throughout Antarctica micro-organisms such as algae, bacteria, fungi and protozoa play a leading role in the biological transfer of materials and energy. In the extreme portions of this global region, particularly those experiencing near-continuous freezing or very rapid freeze–thaw cycles, higher plants and animals are completely absent and the food chains and biochemical nutrient cycles are entirely microbial. In many antarctic environments, however, human beings and the materials and microbes that we bring with us have generated new, additional tests of microbial resilience (see Chapter 11).

Perhaps the greatest challenge that microscopic communities in Antarctica may face will be the environmental shifts induced by perturbations of the Earth's atmosphere. Current climatic models that examine the effects of man-induced increases in atmospheric CO_2 and other gases predict a 0.5–2 °C warming of the temperate zone, and a more pronounced warming in the polar regions, by the middle of the next century (e.g. Schlesinger, 1986). An increase of the ground level temperatures in Antarctica by only a few degrees Celsius would alter the seasonal balance of freezing and

melting, with potentially greater ecological repercussions than elsewhere in the biosphere. Human influences on the ozone layer and the resultant increase in ultraviolet radiation particularly in the Antarctic (e.g. Farman, Gardiner & Shanklin, 1985) may also induce strong responses at the microbial level, and cause further shifts in genetic diversity.

True endemism appears to be relatively rare amongst the antarctic microbiota, but the environments of this region have selected for a wide range of robust microbial assemblages. The following chapters explore the structure of these assemblages, the chemical and physical properties of their surroundings and the interactions at both a population and cellular level between the microbiota and their antarctic habitats.