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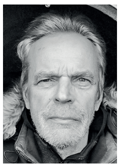
THE HISTORY OF GLOBAL GLACIATIONS

The most extraordinary thing in the Universe is inside your head.

Bill Bryson



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According to an informal definition, a global glaciation occurs when both of Earth's poles are covered in ice. In geological history, such global glaciations have represented episodes where Earth has seemingly "rebelled" against the Sun, which, with the support of a greenhouse atmosphere and the heat-buffering ocean, has generally maintained temperatures above 0°C for billions of years. Yet, three times, Earth's poles have dipped below water's freezing point: first, 2.2 billion years ago (during the Huronian glaciation), then again 0.6 billion years ago (the Cryogenian glaciation), and finally in the Neogene (the Neogene glaciation), beginning 23 million years ago and continuing to the present day. In the Carboniferous period (around 360–300 million years ago), ice sheets are also known to have covered the southern polar region of the supercontinent Gondwana, though evidence of northern ice cover from this time is absent. Outside of these cold snaps, Earth's temperature has remained relatively stable, as the Sun has grown larger and greenhouse gas concentrations have fallen.

Each such global glaciation has brought about immense environmental stress but also served as a boost to evolution. After the first glaciation, oxygen-utilizing organisms emerged on Earth, developing aerobic metabolism; after the second, the biosphere filled up with myriad multicellular organisms. The third global glaciation ultimately led to the rise of *Homo sapiens*, whose brain functions with the efficiency of a supercomputer and possesses virtually limitless operational memory. This cognitive leap forward allowed us humans, alone among living creatures, to unlock the mysteries of procreation and even

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Thala Bay, East Antarctica, offers us an analogue of what a sunset looked like on the shores of Gondwana in the Carboniferous Period (about 300 million years ago)

venture to the Moon. Evolution outdid itself, creating a biocybernetic system capable of understanding itself. But how did something so extraordinary come to exist in nature?

The birth of the Earth

Today's terrestrial environment is the result of a long history of interactions among the Earth's lithosphere, hydrosphere, atmosphere, and biosphere. The first three formed directly after the collision of two proto-planets (proto-Earth and Theia), an event that gave rise to the Earth and Moon around 4.5 billion years ago. Soon after, the Earth developed a structure similar to its present form, with a liquid iron core about the size of Mars at its center, generating a geomagnetic field. This core was surrounded by a mantle of moderately dense rock, while the lightest rocks, including those of the continental crust, formed the outer lithosphere. As the planet cooled, the original magma ocean gave way to an ocean of water that covered Earth entirely, making it a true water world (a concept Hollywood's "Waterworld" would strive to depict over 4 billion years later).

The biosphere began forming in this primordial ocean. Exactly when life originated is uncertain, but the earliest known microfossils date back to the Archean eon (3.5 billion years ago), and inclusions of "light" graphite (a marker of organic material) in zircons have been dated to around 3.8 billion years ago, with some individual crystals dating to as far back as 4.1 billion years. The very first self-replicating organisms may thus have arisen during the late Hadean eon (4.55–4 billion years ago). The emergence of each successive species tells a story of evolutionary chance, with survival depending on adaptability to the changing environment. In the Hadean, Earth's atmosphere was dense, consisting mainly of water vapor, ammonia, carbon dioxide, sulfur oxides, methane, and trace noble gases. Free oxygen was absent. The planet was wreathed in clouds, and surface pressure was about 60 bars – significantly higher than today's atmospheric pressure of approx. 1 bar.

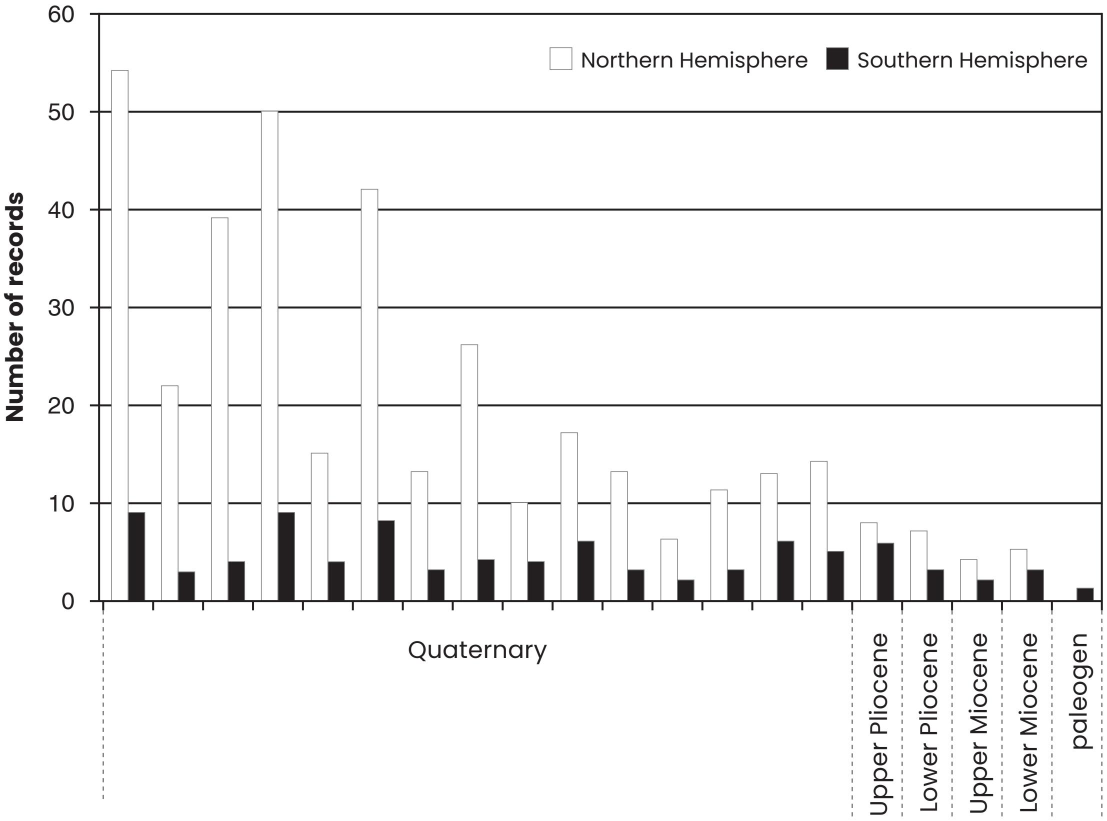
In the Paleoarchean (3.6–3.2 billion years ago), single-celled organisms (prokaryotes) were *chemotrophs* – deriving energy from chemicals in their immediate environment to divide into daughter cells. By the Mesoarchean (3.2–2.8 billion years ago), however, bacteria with more efficient metabolisms had appeared. These organisms could process atmospheric CO_2, producing CH_4 (methane) as a byproduct – a process called methanogenesis. These early bacteria reshaped Earth's atmosphere, changing it from CO_2-rich to methane-rich. With the Sun still young, this methane-heavy atmosphere kept Earth's surface temperature above freezing.

But it was at this point that organisms possessing a game-changing organic compound – chlorophyll – emerged. Cyanobacteria, equipped with chlorophyll, began photosynthesizing CO_2 and releasing oxygen as a byproduct. Shallow-water cyanobacterial mats (stromatolites) are evidence of the crust's first emergence above the ocean's surface, marking a pivotal event. From that moment on, the lithosphere came into contact with the atmosphere, a shift that would have enduring effects on the global climate.

Initially, oxygen remained dissolved in the water, primarily binding with iron ions. It was only when these were depleted that oxygen began to escape into the methane-rich atmosphere. The effect was profound. Around 2.2 billion years ago, atmospheric methane rapidly oxidized to carbon dioxide, which is a much weaker greenhouse gas. At that time, the Sun

The Bunger Hills (East Antarctica) are an analogue of the Earth during the Huronian Glaciation (2.2–2.1 billion years ago)

ADAM NAWROT



Frequency of Antarctic (black bars) and Arctic (white bars) glaciations, from the Miocene (about 23 million years ago, right side of the horizontal axis) to the present. An increasing trend in global cooling is evident, expressed by the rising number of glaciations in the freezing Arctic (after: Ehlers & Gibbard 2007)

emitted several percent less energy than it does today, so the decrease in methane concentration in favor of CO_2 triggered a severe freeze. The Earth froze to the depths of the lithosphere, experiencing its first global glaciation, known as the Huronian Glaciation. Today, East Antarctica serves as an analogue for Earth's surface during that period.

Around 2.1 billion years ago, the ice began to recede – likely due to heat accumulating in the lithosphere from within the Earth, along with developing tectonic and volcanic activity. For the next billion years, a period of "great geological boredom" ensued. However, photosynthetic organisms were not idle; they systematically drew down CO_2 from the atmosphere while enriching it with oxygen, simultaneously creating increasingly complex multicellular structures.

Chlorophyll played a crucial role in sequestering CO_2 from the atmosphere. However, as intensified global tectonic activity brought about colliding continents and the uplifting of mountains (known as *orogeny*), more rocks began to chemically react with the atmosphere. Due to erosion and a process known as *carbonation*, a substantial portion of atmospheric CO_2 became irreversibly bound in inorganic carbonates, leading to a further decline in CO_2 concentration. In the late Proterozoic (1–0.541 billion years ago), following the breakup of the supercontinent Rodinia and subsequent continental collisions, the Cadomian orogeny (0.7–0.55 billion years ago) occurred, resulting in the uplift of additional mountain ranges, whose erosion further enhanced the sequestration effects of carbonation.

Photosynthesis and carbonation curbed the greenhouse effect. However, over geological time, the atmosphere gradually became thinner due to solar winds, which expelled atmospheric gas particles into space over billions of years. This process likely intensified during the late Proterozoic when, for 200 million years, the intensity of Earth's magnetic field temporarily decreased (probably due to the crystallization of the inner core), measuring only about 10% of today's levels. The relentless solar wind could have significantly thinned the atmosphere, thereby reducing its greenhouse effect (without an atmosphere, Earth's temperature would today be around –15°C). The combination of these three factors led to the second global glaciation (in fact, a series of successive glaciations), known as the Cryogenian Glaciation (0.85–0.635 billion years ago). However, it was not as extensive as the Huronian Glaciation, as the growing Sun was supplying more thermal energy (though not yet as much as it does today). Today's rocky oases in Antarctica serve as a good analogue for what the Earth was like back during that time.

When the ice melted

The end of the Cryogenian Glaciation marks a significant turning point in the evolution of living matter. The cold, well-oxygenated ocean (as described

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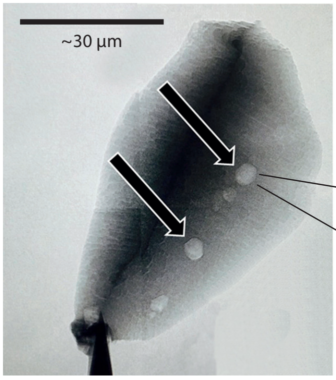
An Antarctic analogue of what the Earth's equatorial zone was like during the Cryogenian Glaciation (0.85–0.635 billion years ago)

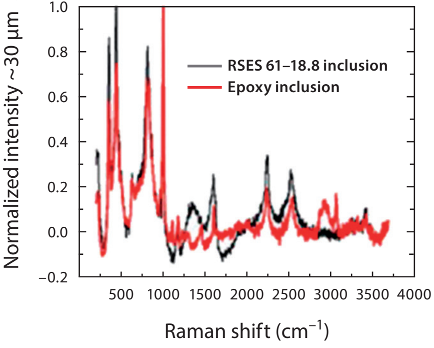
by Henry's law, which states that the solubility of gases in liquids is inversely proportional to the temperature) became a nurturing ground for the emergence of complex multicellular organisms. With the onset of the Cambrian period, skeletal organisms began to appear as well. Among these were heterotrophic forms that metabolized food using oxygen, giving rise to the animal kingdom, which initially consumed algae and later began to prey on one another. Today, animals constitute a small fraction (less than 0.5%) of Earth's total biomass. Plants dominate, accounting for about 80%, while the remaining biomass consists of bacteria, fungi, archaea, and protists. The contribution of humans to global biomass is estimated to be around 0.01%.

During the Silurian period (approximately 443–419 million years ago), the first plants appeared on land, significantly increasing the potential for atmospheric CO_2 sequestration, which peaked during the Carboniferous period (359–299 million years ago). At that time, CO_2 levels dropped to their lowest since the atmosphere's formation, while oxygen levels were twice as high as they are today. Concurrently, the Variscan orogeny occurred, intensifying the carbonation process. Carbon dioxide nearly disappeared from the atmosphere, leading to the development of ice sheets across vast areas of the paleocontinent Gondwana. The carbon captured by Carboniferous plants was kept stored away in by the Earth for 300 million years – until it came to be tapped by humans.

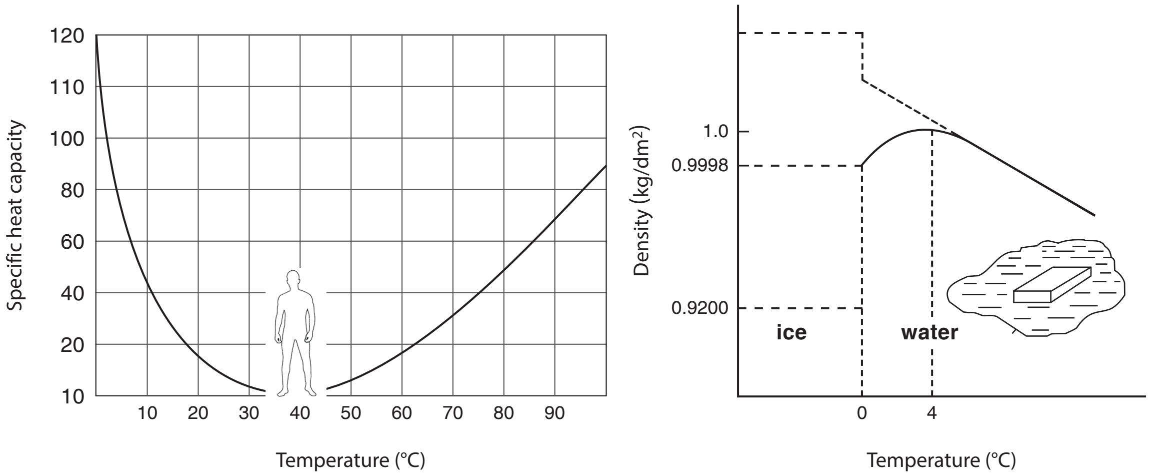
The Permian-Triassic period (299–201 million years ago) was marked by major extinctions, including among plants. As a result, the atmosphere could renew its CO_2 resources, primarily due to volcanic activity. Terrestrial plants gradually made a comeback as CO_2 consumers. Grasses and forests developed, and by the Eocene (about 50 million years ago), spores from the fern *Azolla* covered the Arctic Ocean. At the beginning of the Miocene (23 million years ago), oaks and



Transmission X-ray image of a zircon sample (approximately 4.1 billion years, Jack Hills exposure, Australia) with graphite marked



Inset: Raman spectra for the upper inclusion and an "epoxy inclusion" from another zircon crystal, indicating the differing spectral characteristics for graphite and epoxy resin (after: Bell et al. 2015)



Diagrams illustrating selected properties of water: variability of specific heat capacity (Pc, on the left) and density (on the right). The silhouette of a human indicates the optimal value from the perspective of enzymatic reaction kinetics (after: Filin 2017)

sequoias still populated Spitsbergen. The Earth was warm and green, basking in the rays of an increasingly powerful Sun. So why did it happen that, over the past few million years, Earth's poles became covered in ice again, with temperatures dropping by nearly 60°C?

Unless unknown astronomical factors are at play (incidentally, the well-known Milankovitch cycles turn out not to have significantly influenced the Neogene temperature decline, as indicated by ice core research from Antarctica and Greenland), the blame for the historically low concentration of CO_2 can be attributed to both photosynthesis and carbonation, along with the already thin atmosphere. Overall, radiative forcing became critically low, and so it should be no surprise that any change in atmospheric CO_2 concentration has a significant impact on our planet's climate today.

Homo sapiens – a child of chill?

The peak of temperature decline on the Earth has occurred during the last five million years. At the same time, there has been an evolutionary flourishing of primates. DNA studies suggest the possibility that the appearance of a mutated gene called *ARHGAP11B* in *Homo erectus* approximately 300,000 years ago may have significantly altered the course of hominid brain evolution by increasing its volume.

The number of mutations occurring daily in our bodies is immense; however, mutated cells are usually eliminated by the immune system. If biochemists' suggestions about the possible role of the *ARHGAP11B* gene are correct, then the first individual with this mutation survived initial scrutiny by their own immune system and managed to thrive on the African savanna (which was far from certain at the time) until reaching sexual maturity. Subsequent generations of this mutant could develop in a natural environment optimal for a growing brain, providing access to oxygen, water, and energy sources (food). However, I believe that ambient temperature was also fundamentally important, allowing the entire organism to function effectively. The body operates best at a temperature of 36.6°C, which is the healthy temperature for a human, close to their thermal comfort level without clothing.

Why this specific temperature? The answer lies in the kinetics of biochemical reactions in the human body. Enzymes, the catalysts of these reactions, are most effective within a temperature range of 35–42°C. A practical example can be found in enzymatic laundry detergents. They are ineffective at temperatures above 42°C because the enzymes denature. Conversely, at temperatures below 35°C, enzymes lack sufficient kinetic energy to participate effectively in chemical reactions.

The optimal conditions for enzymatic reactions derive from the properties of water, which exhibits nonlinear variability in specific heat capacity and reaches a minimum around 37°C. It is at this temperature that enzymatic reactions occur with the highest intensity, making the organism most efficient.

We cannot change the properties of water, which constitutes 60% of our bodies, or those of the proteins that make up most of the rest. Due to the physicochemical characteristics of the human body, we thus find ourselves in a kind of thermal trap. Our supercomputer (i.e. the brain, the human body being a battery to sustain its operation) operates efficiently only within a narrow temperature range. And this range only emerged on Earth with the onset of the third global glaciation.

We are, therefore, children of global coldness. If anyone has doubts, I invite you to turn off your refrigerator after reading this essay and imagine a world where the temperature consistently stays above 0°C, much like it generally was on Earth for millions and millions of years. ■

This article is based on lectures by the author over the last ten years, delivered at the Faculty of "Artes Liberales" at the University of Warsaw, at the interdisciplinary doctoral programme of the Polish Academy of Sciences, and Universities of the Third Age.

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