The emergence of the climate-system

From analysis of lead isotope ratios the Earth is thought to be between 4.5-4.6 billion years old, the same age as the the solar system itself. If the Earth did indeed receive a blow of the scale that is thought to have formed the Moon, it would have made the Earth a very hot place. From the many craters observed on the Moon, Mars, and Mercury, the early years of the planets were likely marked by frequent and large impacts by comets and asteroids. The energy released from such impacts may periodically have evaporated all water on the planet, which would then have remained in the atmosphere as steam. No rock remains from the early years on Earth as it was recycled in the interior, the earliest rocks appear around 4.2 billion years ago. The Hadean period from 4.6-3.7 billion years ago was characterised by volcanic activity and a large greenhouse effect as there was a high concentration of carbon dioxide in the air. In those times almost all the free oxygen would have been removed from the air by chemical reaction (it was a *reducing* atmosphere). Other gases in the atmosphere would have been nitrogen, water vapour, carbon monoxide and hydrogen.

The presence of this last gas, hydrogen, in the early atmosphere is interesting because it poses the question: how come there is still water on our planet today? Furthest out in the atmosphere hydrogen gas breaks down into atoms which are too light to be held by the pull of Earth's gravity, and hence there is a steady loss of hydrogen into space. On early Earth water would have reacted, e.g. with iron, to sequester the oxygen and release hydrogen gas. Eventually such processes would remove all of the hydrogen available to form water molecules and the entire planet would dry out. This is probably what happened to our neighbours Mars and Venus – we are pretty sure there was once water on these planets too. So what happened? Although we are not sure exactly when, we know for sure that another process entered the stage: life. Life would have retained water in two ways. Firstly, micro-organisms retained hydrogen produced from the reaction of water with rocks on the sea floor. By turning hydrogen into hydrogen sulphide these micro-organisms gained the energy needed to sustain themselves. Secondly, photosynthesis would have released more oxygen which would then have been available to react with gaseous hydrogen to produce water (also oxygen is a source of the highly reactive hydroxyl radical which acts as a kind of vacuum cleaner of the atmosphere by reacting with all sorts of gases and, importantly, pollutants). Both processes slow down the loss of hydrogen to space, and were likely to play a crucial role in retaining Earth's water reservoir.

The origin of life might always remain shrouded in mystery. Guesses from scientists encompass the formation of organic molecules by lightning in a 'primordeal soup', at hydrothermal vents on the bottom of the ocean, on radioactive beaches, inside the Earth's crust, and in space. The beginning of life seems almost as mysterious as the beginning of the universe itself. Just like matter appeared out of an infinitely small point, life appeared out of matter. Nevertheless, it appeared, and however we look at it, life is just as integral a pattern to the universe as atoms, planets and galaxies. The emergence of life completely changed the scene on Earth: from a world ruled by the simple mechanics we often picture as a game of billiard emerged the bacteria, the smallest living entity we know. With the evolution of life a process began that transformed the planet from a ball in a game of billiard into a self-regulating system unlike any other planet in the solar system. A planet of multi-cellular organisms, ecosystems, consciousness and space travels.

But we are getting ahead of ourselves now. By the onset of the Archean period 3.7 billion years ago early bacterial life forms emerged and photosynthesis began on a large scale. As mentioned earlier, we expect that there was a much higher concentration of carbon dioxide in the atmosphere at that time. The carbon dioxide would have come from volcanism and what is known as 'impact degassing' – the release of carbon dioxide from rocks as a consequence of planetesimal bombardment. This helped keep the surface of the planet warm by recycling energy from the Sun in the atmosphere, the famous greenhouse. The sun is powered by nuclear fusion, a process that fuses four hydrogen nuclei into one helium nucleus in the Sun's core. This heats up the core, which increases pressure and keeps the Sun stable (one helium nucleus takes up less space than four hydrogen nuclei and thus exerts less pressure). When temperature rises chemical reactions increase, as does energy emitted from the surface. This means that the Sun would have been about 30% less luminous when the Earth formed and less energy would have been available to keep the planet warm (this is known as the "faint young Sun paradox"). In fact, had the energy from the Sun's rays not been recycled in the atmosphere the oceans should have been giant ice-caps prior to two billion years ago. We know from the sedimentary rock record that liquid water has been around for much longer than that. A high concentration of carbon dioxide, and therefore a larger greenhouse effect, would have recycled the heat that was needed to keep the Earth from freezing (and solved the faint young Sun paradox).

The high concentration in atmospheric carbon dioxide diminished concurrently with the increasing luminosity of the Sun and at a pace that kept surface temperatures right for life. When photosynthesising organisms colonised the planet, life began to play an increasingly active part in climate regulation. The transfer of carbon from the atmosphere to reservoirs in the solid Earth is greatly enhanced by biological productivity. Atmospheric chemistry is affected by the biota in a multitude of ways, we shall just mention one of these here to conclude the Archean period. As mentioned before, Earth's atmosphere was for a long time reducing, that is, oxygen levels were close or equal to zero as it was removed by organic matter, reduced gases like methane, or reduced substances at the surface. The amount of oxygen in the atmosphere depends on the balance between its production and removal. Towards the end of the Archean, about 2.5 billion years ago, a decline in the rate of reduced substances, due to diminished tectonic and volcanic activity, meant that oxygen began to dominate the atmosphere – an increase in atmospheric oxygen (the O_2 in the CO_2) comes from the burial of organic carbon (the C) in sediments. Free oxygen in the atmosphere did not appear until around 2.2-2.0 billion years ago when larger plants and animals had evolved and the rate of burial of organic matter grew. The change to an oxygen-rich atmosphere produced a vast range of new ecological niches in which new life forms could evolve.

The appearance of life on Earth altered the chemical composition of the atmosphere; except from a few inert gases, which account for around 1 per cent, all the gases in the atmosphere are in exchange with organisms. Thus the biota plays a fundamental role in the self-regulation of the Earth system and in the stability of climate over long time scales. Before we take a closer look at how this system and its components work, it is necessary to take a look at the conceptual tools we use to understand the functioning of the system, and to see how these tools themselves are part of the ongoing story of our collective knowledge.