Chapter 8

Back to Earth

There is a set of terrestrial planets that we can study much closer to home. They are separated from us not by space but by time. Our planet has been around for 4.6 billion years, about a third of the total age of the Universe (13.7 billion years). Throughout its long life, it has changed so much that, were we to be transported to one of its past incarnations, it would appear as alien as an exoplanet.

The Earth has been in turn a lava planet, an ocean planet and a snowball planet. The main constituent of the air has been successively hydrogen, water vapour, carbon dioxide, and finally nitrogen. The pressure at the surface has risen to hundreds of bars before falling again to the one bar to which we are accustomed.

Today we could say that the Earth is having some sort of mid-life crisis, because one species on its surface has been busy burning vast quantities of buried carbon and fossil fuels, thus abruptly increasing the carbon dioxide content of the atmosphere.

And the story is not over. We are only mid-way through the life of the Sun, and more dramatic changes to the Earth's atmosphere are in store.

Let us now journey through some of the stages of the Earth's rich history, which has been painstakingly reconstructed by a motley crew of geologists, geophysicists, biologists and astrophysicists.

But first, to tell the history of the Earth we need a more convenient unit of time than years, which are just too small. Planets evolve over hundreds of millions of years, the duration of geological epochs. There is no convenient name in English for hectomegayear, and we have to resort to a geological term: one hundred million years is an *Era*. Our planet is now 46 Eras old, in ripe middle age. The dinosaurs roamed the planet one Era ago. Earth's life expectancy is about 90 Eras, at which point the Sun will inflate into a red giant star and die[16].

Let us leaf through the family photo album and look at Earth at ages one, five, 24, 40 and 46 Eras.

Birth pangs

When the young Sun became bright enough to blow away the disc of gas that surrounded it at birth, it was left with a procession of planets. There were at least four gas giants far away, so hot that they shone like small stars. Five red-hot balls of lava orbited closer to the Sun. Starting from the Sun these unruly children were Mercury, Venus, Earth, Theia, then Mars.

Earth's atmosphere was made up mostly of hydrogen and helium captured from the disc of gas. But because these two elements are so light, they leaked out of the atmosphere into space at a steady rate.

Then one morning, around 4.4 billion years ago, young Earth was hit by the Mars-sized planet Theia. The cores of the two planets merged, but enough magma was thrown out by the collision to form the Moon. This event was so violent that no rock would have been left unturned, or more accurately unmelted, so that the Moon-forming impact can be taken as the true birth date of "our" Earth. Amazingly, the whole catastrophe lasted less than a day, the most memorable day in Earth's history.

The Moon impact suggests why the atmospheres of Earth-like planets around other stars may be very different from that of Earth, even at the earliest stages. The details of the last impacts can completely modify the outer crust of a rocky planet and the amount and types of gases available to form the atmosphere.

Early in its life, the Earth was a "lava planet", entirely covered with an ocean of liquid molten rock.

Some exoplanets remain covered with lava all their life, because they orbit so close to their star that the temperature remains hot enough to melt rock. But the nascent Earth cooled quickly. Soon, bits of crust formed, like the crust on lava flows in volcanic places like Hawaii. Because solid rock can hold less gas than molten lava, the gases contained in the rocks escaped. These volcanic gases, mainly water, carbon dioxide, and sulphur, formed the second atmosphere of planet Earth – after the atmosphere of hydrogen and helium left over from the disc of gas around the Sun. For a few million

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[16] Accidents may happen to shorten this lifetime, such as a very close encounter with another star that perturbs the orbits in the Solar System, but such encounters are extremely rare because the space between the stars is so vast. There is also the small possibility of the orbit of Mercury becoming unstable, see page 107.

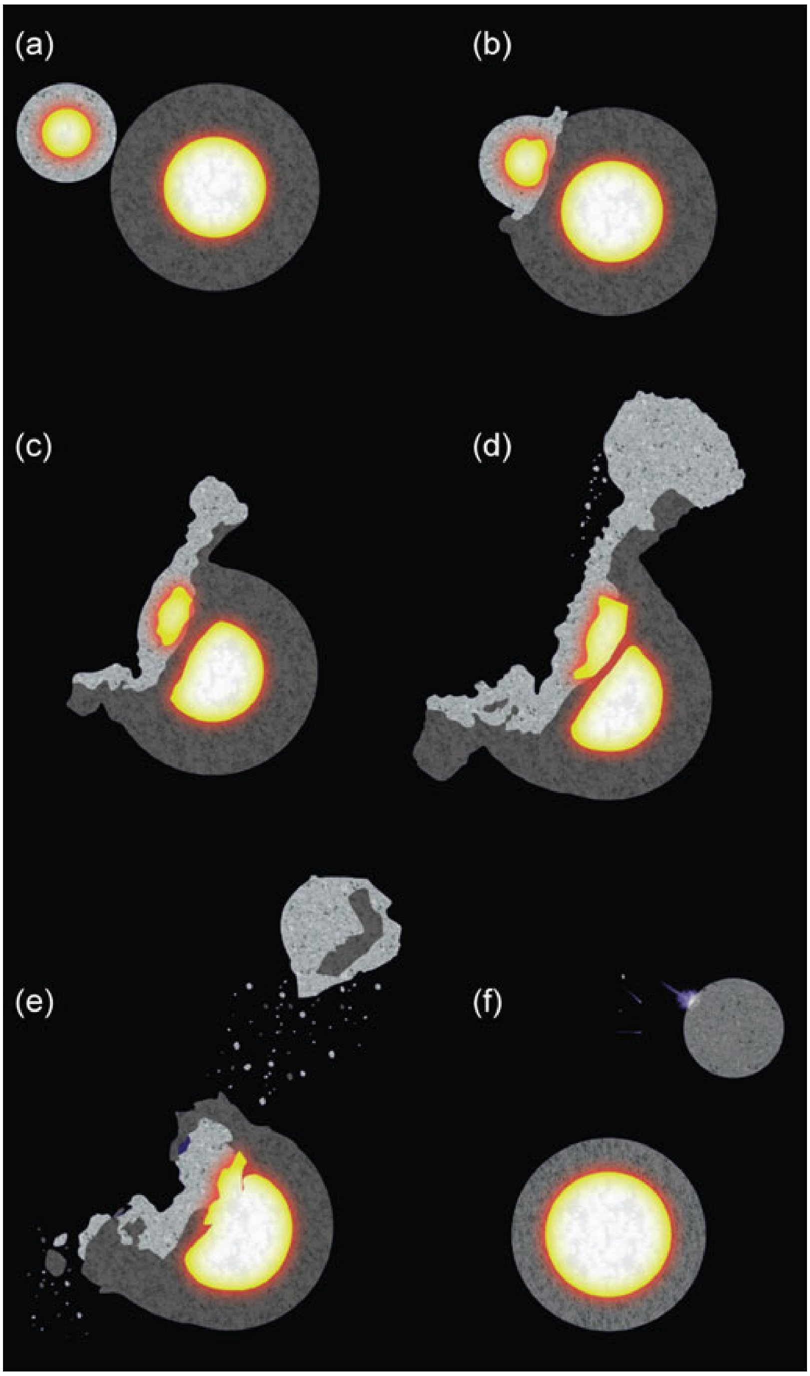

Fig. 8.1 26 April, 4370426528 BC, 3:12 AM: moon-forming sequence of events. Image credit: James Symonds

years, the surface of the Earth was a patchwork of lava pools and drifting rafts of recently solidified rock, shrouded in steaming volcanic fumes.

This epoch is referred to as *Hadean* by geologists, after Hades the god of hell, and hell is what the place looked like, with raw lava, boiling sulphur lakes, volcanoes and craters. The atmosphere was an extremely thick brew of carbon dioxide, water vapour and sulphuric acid, laced with dust and soot. Most of the water in the future oceans was still in the air in the form of water vapour, so that the atmosphere as a whole weighed hundreds of times more than today. In fact the pressure at the surface of the planet was similar to that at the bottom of the ocean today, because the pressure depends only on the amount of material overhead, and the weight of water is the same whether it is in liquid or vapour form – vapour just takes vastly more room.

With so much water and carbon dioxide, the greenhouse effect was intense, and the surface temperature was similar to that of present Venus.

Young Earth had become a "steam planet", like some ocean planets that orbit close to their star. The atmosphere, dominated by water, transitioned smoothly from vapour to hot, high-pressure liquid, because the temperature was too high for a well-defined "sea surface" to form (see the phase diagram of water on page 74).

Later meteoritic impacts and lava flows destroyed all trace of this remote epoch in the geological records, and very few pieces of the puzzle remain for geologists to study. On the Moon this epoch can be studied far more clearly, because ancient craters and lava flows have been left untouched.

Earth at 5 – ocean planet

The planet kept cooling, because it still produced much more heat than it received from the young Sun[17]. At some point the temperature dropped low enough at the top of the atmosphere for the first drops of liquid water to condense, forming clouds. Rain began to fall, starting a cycle that is still ongoing more than 4 billion years later.

At first the rain evaporated before touching the ground, because the lower atmosphere was still very warm. But inexorably, pools formed, then lakes, then seas and oceans, until most of the water had condensed out of the air, and the whole planet was covered by a global ocean three kilometres deep on average.

The rain also took out the sulphur from the atmosphere, since sulphur can be dissolved into water as sulphuric acid. The rain in early Earth was acid rain.

Earth had become an "ocean planet". For the first time, it looked Earth-like, with its global blue seas. Its atmosphere of carbon dioxide was still very thick (between two and ten times the present pressure, we are not sure), and rendered opaque by the dust and haze from the volcanic fumes.

Over the next few Eras, landmasses surfaced from the oceans: some volcanoes that erupted from the inside of the Earth were large enough to emerge, like Hawaii, the Canary Islands or the Galapagos today. Some slabs of lighter rocks floated higher on the magma, like a cork on water, to form the first continents.

The rock-carbon cycle, the cycle that integrated the CO_2 in the atmosphere into sediments on continents and under the sea, was very active, and started nibbling away at the carbon dioxide in the atmosphere. Over time, most of the CO_2 was removed from the atmosphere, until nitrogen became the dominant gas.

Somewhere deep in the ocean, around some submarine volcanoes, a strange chemical process got underway. Little pockets of complex carbon molecules started spreading. Basking in the hot water, these primitive cells used the sulphur from the volcanoes to extract chemical energy and prosper.

The water in the ocean was very warm, above 60 degrees Celsius. Early bacteria were thermophiles, which simply means that they liked heat, and could make themselves at home in this global ocean. Over time some of them evolved to master an amazing

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[17] At the distance of the Earth, the temperature at which heat loss by infrared radiation and heat gain by sunlight balance each other is around zero degrees Celsius.

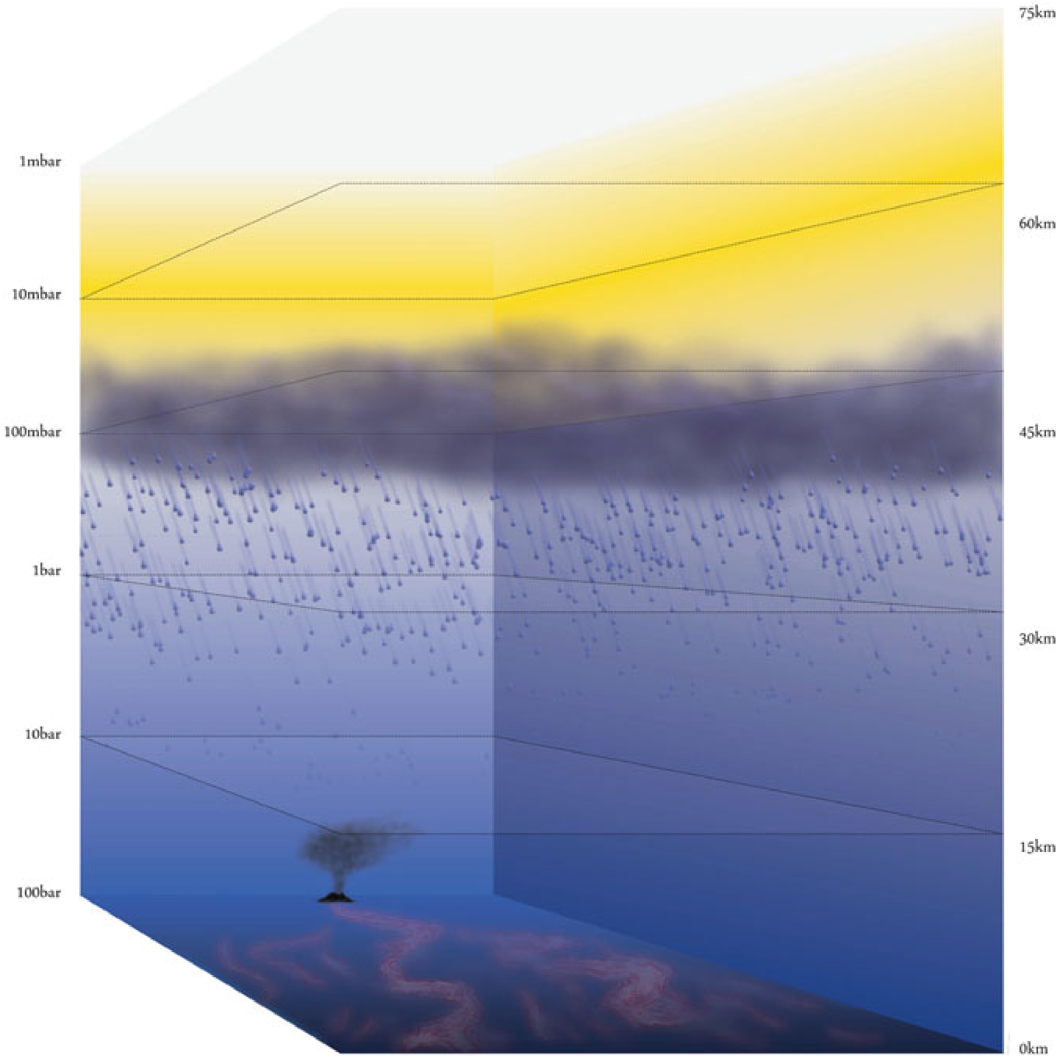

Fig. 8.2 Atmospheric profile of young Earth.

chemical trick: they started using the energy of the Sun instead of the chemical energy of submarine volcanoes and photosynthesis was invented. This allowed them to spread over the whole global ocean, and from then on, life became a factor to be taken into account in the evolution of the Earth's atmosphere.

The engineering of planet Earth by life had started.

Earth at 24 – oxidation and snowball

At 24 Era, 2.2 billion years ago, Earth was a "snowball planet". It was covered by ice and snow from pole to pole, its atmosphere frigid and quiet.

We claimed in Chapter 7 that the climate of Earth was stable in two states, "warm" and "snowball". But what nudged it from one state to the other 2.2 billion years ago?

Apparently, this was the fault of the bacteria that took control of the climate. Photosynthesis breaks water molecules to use their hydrogen atoms as electron donors, and reject the oxygen in the atmosphere; and the oxygen that composes 20 percent of the present atmosphere of the Earth was entirely produced as a poisonous byproduct of bacteria and plant photosynthesis. The bacteria which perfected this great chemical feat, the cyanobacteria (called blue-green algae in English, although they are not algae) colonised the oceans, and started rejecting free oxygen on a planetary scale. They were helped in this by the fact that free oxygen was highly poisonous to other forms of life which had not perfected the trick of photosynthesis. Collectively, cyanobacteria produced so much oxygen that from that moment on all the metals at the surface became oxidised. The arrival of photosynthetic cyanobacteria is marked in the geological records by the disappearance of metallic iron formations in the rocks and the global dominance of rust. But the oxygen content in the atmosphere did not rise at the beginning of the era of cyanobacteria. At first, there were enough minerals and metals to oxidise on the ground for all the oxygen produced to be immediately returned to the rocks.

Only when most rocks were finally oxidized did the content of free oxygen in the atmosphere start to rise, to about 0.1 percent. Oxygen-using bacteria started appearing, as well as more complex, but still single-celled life forms.

As soon as oxygen became sufficiently abundant, it cleared the methane out of the atmosphere. Methane is a very efficient greenhouse gas, and oxygen is not, so this caused a global drop in temperature – enough to nudge the planet into a positive feedback loop (increasing white snow and ice cover causing more sunlight to be sent back into space, which cooled the planet and further increased the snow cover) that lead to the snowball-Earth episode.

The Earth was now a frigidly cold planet, almost entirely covered by a giant ice sheet. Only one patch of ocean remained clear of ice near the Equator. Life struggled to survive near the ice margin and in the open oceans. Close to the poles the temperature was forbiddingly low throughout the year.

Earth at 35 – the boring billion

At 35 Eras, we catch the Earth in what geologists call “the boring billion”, because nothing much happened to the rocks in a billion years.

The planet had recovered long ago from the snowball episodes. It was saved by the volcanoes. The ice covering the land and oceans blocked the rock-carbon cycle: the carbon dioxide in the air could no longer be integrated into rocks. But the other side of the cycle – the injection of CO_2 into the air by volcanoes – kept on going; volcanoes had no problem piercing through ice, as they do in Iceland today. Over time, the carbon dioxide concentration in the atmosphere slowly increased, until the greenhouse effect was high enough to melt the ice again.

The oxygen content in the atmosphere was stable at around 0.1 percent. This was not enough to produce an ozone layer. Therefore the stratospheric lid that kept the clouds below ten miles in the present Earth did not operate.

Convection must have extended much higher into the atmosphere. This would have been called “the Great Age of Clouds” by any visitor, since the high temperatures, large oceans and lack of stratospheric lid would have produced the most magnificent cloud formations and the most awesome storms.

During this stage, Earth was a living planet, recognisably Earth-like with oceans and continents, and vast colonies of blue-green algae. Life had been present for at least three billion years, yet there was no signature in the atmosphere that would make it detectable for an alien astronomer. This is a sobering thought in the search for inhabited exo-Earths: life on our own Earth has been chemically discreet for 90 percent of its tenure.

The convective motions in the Earth's mantle pushed the continents around, and every few hundred million years, they gathered together in a single super-continent, then they broke up again into half a dozen pieces or so. The last super-continent was Pangea, where the dinosaurs roamed. At 35 Eras, landmasses gathered into one such super-continent, Rodinia.

Continental drift provides the second half of the rock-carbon cycle, the one that allowed the Earth to recover from the snowball episodes: oceanic plates are buried into the Earth's mantle by tectonic motions. The carbonates that they contained are burnt and turned back into CO_2, which escapes from the volcanoes back into the atmosphere. By modifying the amount of volcanic activity, as well as the surface of land available for the formation of carbonates, the shape and displacement of continents modifies both sides of the rock-carbon cycle, and therefore influences the amount of CO_2 in the atmosphere and the evolution of the climate (in addition to the more obvious direct effect on weather and sea currents, see Chapter 7).

Earth at 40 – animal planet

Finally, around 6 Eras ago (at 40 Eras), the level of oxygen had risen sharply again, until it reached 20 percent of the total. We have become used to such air, but as we realised in Chapter 1 this is really a massively explosive atmosphere.

A new type of large organism called plants evolved to take advantage of such an oxygen-rich atmosphere. During the day they used sunlight to produce energy and exude oxygen (like cyanobacteria), but during the night they breathed oxygen and burnt it as a further source of energy. Another class of organism, that we call animals, lived entirely on the free oxygen. They survived by feeding on the plants and using some of the oxygen rejected by photosynthesis to power their high-activity lifestyles.

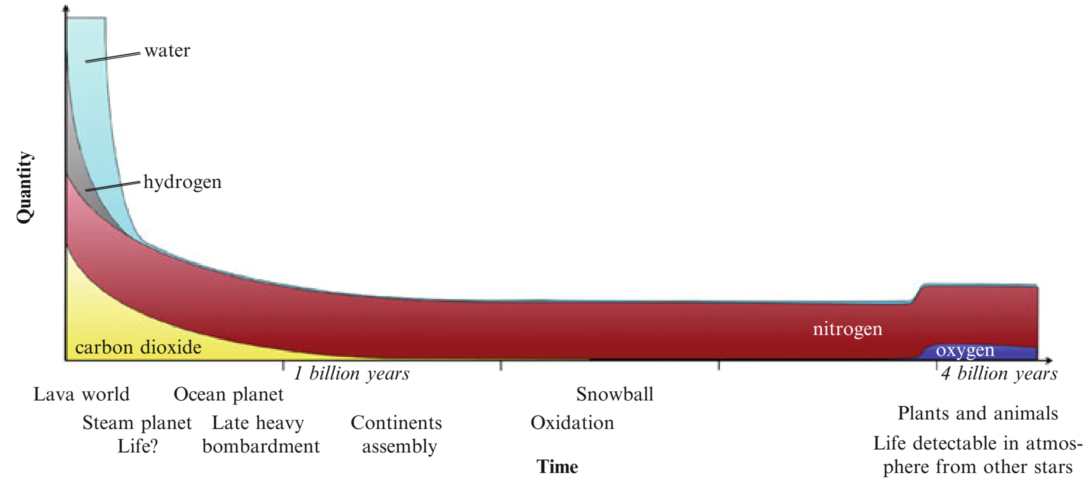

Fig. 8.3 Evolution of the composition of Earth's atmosphere over time.

Fig. 8.4 Earth at 40.

Incidentally, it is interesting to realise that animals had no impact at all on the composition of the atmosphere[18].

About 3 Eras ago (Earth is now 43) we arrive at the kind of world that most animals have known. The continents have finally been colonised by life, giant vertebrates roam the land (the dinosaurs are still in the future). Because there is still more CO_2 in the air, the climate is warmer than today. Both poles remain ice-free.

Earth at 46 – Ice ages

We now reach Earth at 46 – today. We catch it in the middle of its Ice Ages. It may not look that way to us, but from a global perspective the Earth is now in a short, not particularly warm interval between two Ice Ages. For a few million years, it has been oscillating between slightly colder episodes, when the ice sheets extended over most of Europe and North America, and warmer episodes, with ice mainly over the Arctic and Antarctica. Recall that for most of Earth's history the poles had been ice-free, and, snowball episodes excepted, the Earth has never been as cold as in the present geological era. This is due to the "recent" collision of India into Asia, which started about 50 million years ago (1/2 Era) causing the rise of the Tibetan plateau, which is the dominant tectonic event of our Era. It turns out that the high plateau and the monsoon phenomenon that it triggered are very efficient at increasing the rock-forming part of the rock-carbon cycle. The drop in CO_2, together with other tectonic changes such as the opening of the Drake passage, have lowered the global temperature of the planet enough to keep the poles permanently frozen.

Soiling the pool

However, over the last hundred years, human beings have been pumping CO_2 back into the atmosphere at an incredibly fast rate. So fast that the concentration of CO_2 has doubled in only 16 years, or 0.000016 Era, a geological eye blink. The CO_2 concentration has increased from 150 grammes per tonne in 1850 to 300 grammes per tonne in 2010. This is as it was 60 million years ago, at the dawn of the age of mammals. As it

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[18] With possible exceptions. The first, of course, is when one animal species starts burning fossil fuel and putting carbon buried underground back in the atmosphere. Another one is weirder: recent research suggests that a large part of the marine carbonate rock deposits, such as the White Cliffs of Dover, may result from carbonates precipitated in the guts of fish. Therefore ocean fish may play a part in the carbon-rock cycle and help remove the CO_2 out of the atmosphere.

takes more than a hundred years to heat the ocean, the climate hasn't returned to the temperature it was in the Eocene, not just yet.

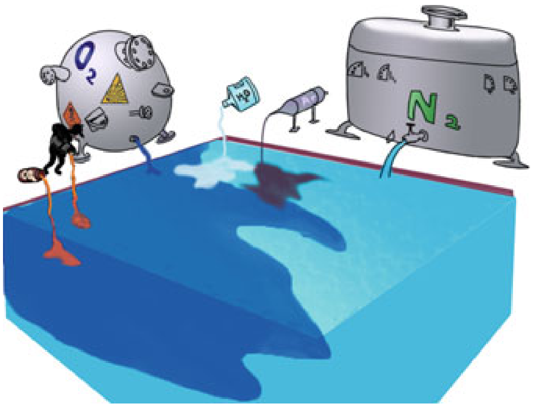


Fig. 8.5 Soiling our pool.

How can such a small amount of gas, less than one part per thousand, have such an impact? Let us think in terms of our "pool" image (Fig. 8.5). A public swimming pool contains about one million litres of water. 100 grammes per tonne is therefore 100 litres. Imagine leaking 100 litres of mildly harmful substance into the swimming pool. It isn't like one swimmer discretely peeing in the pool, but rather like all swimmers doing it for the whole day.

In global terms, human-induced climate change will just be a blip like the Eocene volcanic event. When the injection of CO_2 finally abates, as it has to because the reserve of fossil fuels is finite, the "volcanic" side of the rock-carbon cycle will go back to normal, and the excess CO_2 will be turned back into rocks (not coal and petrol, this time, but calcium carbonates).

Venus is sometimes taken as an example of how global warming could turn very ugly, sending the Earth's climate in a runaway feedback state that would lead to the evaporation of the oceans and the loss of water to space, but we are probably too far from the Sun for that.

Earth's future

Stars like the Sun live for about ten billion years, before turning into red giants. Over their lifetime, they become slightly brighter: the Sun is about 30 percent brighter now than it was for the young Earth, and will be another 30 percent brighter in the next five billion years.

About ten Eras into the future, the oceans will have become so warm that complex life will be cooked. 30 Eras into the future, the oceans will start evaporating, sending the planet onto the "runaway greenhouse" slope leading to a Venus-type atmosphere. The planet will thus retrace some of its steps, a hot ocean, then steam planet, then with a CO_2 atmosphere, until the Sun turns into a red giant star.

Since the death of the Sun probably implies the destruction of the Earth, the story may end here. But for most planets in the Solar System, the demise of the Sun will be only one event among others. The core of the Sun will turn into a white dwarf, and

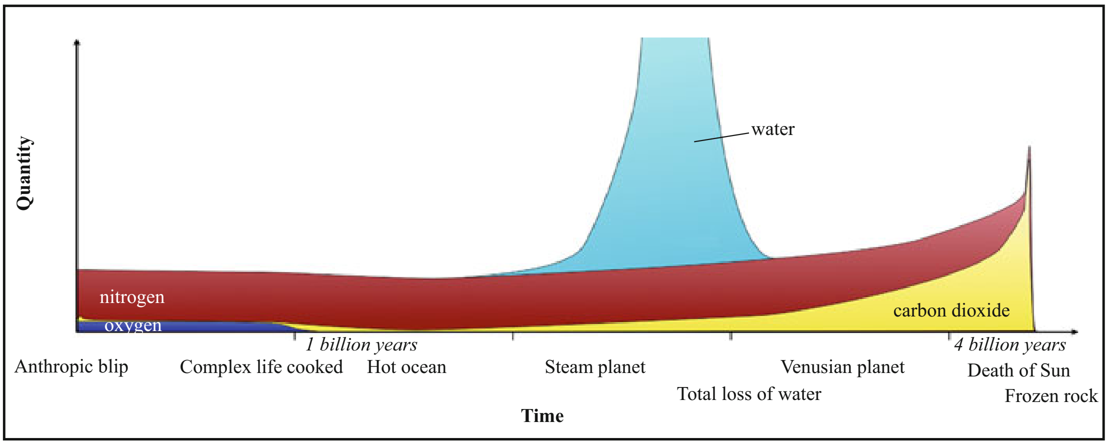


Fig. 8.6 Possible evolution of the composition of Earth's atmosphere in the future.

Mars for instance will keep orbiting it indefinitely. Its atmosphere will freeze out, as will that of Titan.

One interesting twist in the story of the future of the Solar System is that, during the red giant stage, the icy satellites of Jupiter and Saturn will become warm enough for ice to melt, and for water oceans to form at the surface. The red giant stage of the Sun may be short compared to its total lifetime, but it will still last several hundred million years. We may speculate that this is long enough to start life on these planets – it is certainly long enough to see it prosper, if it has already started in the under-ice oceans. The red giant stage of Sun-like stars may therefore offer short abodes for life in the outer edges of planetary systems.

If Earth has had so many incarnations in its long life, what about its close companions? It is harder to reconstruct the ancient climates of Venus and Mars than that of Earth because we have far less data. But as far as we can see, it is clear that both planets were also very different in the past compared to what they are now.

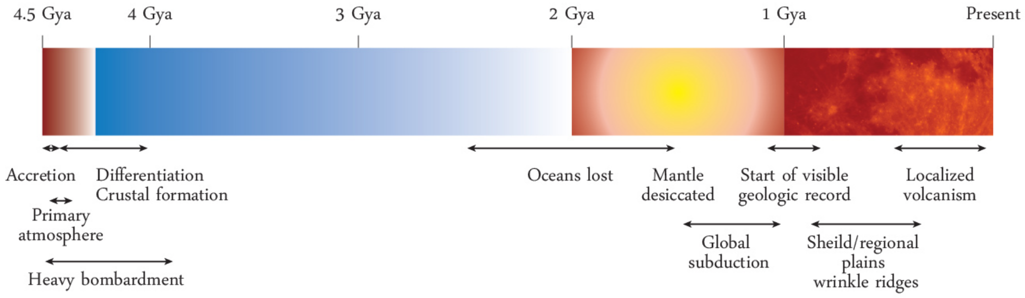


Fig. 8.7 A possible reconstruction of the evolution of Venus. Some specialists think that Venus could have been covered by water oceans for the majority of its life, losing them relatively late. Image credit: David Grinspoon

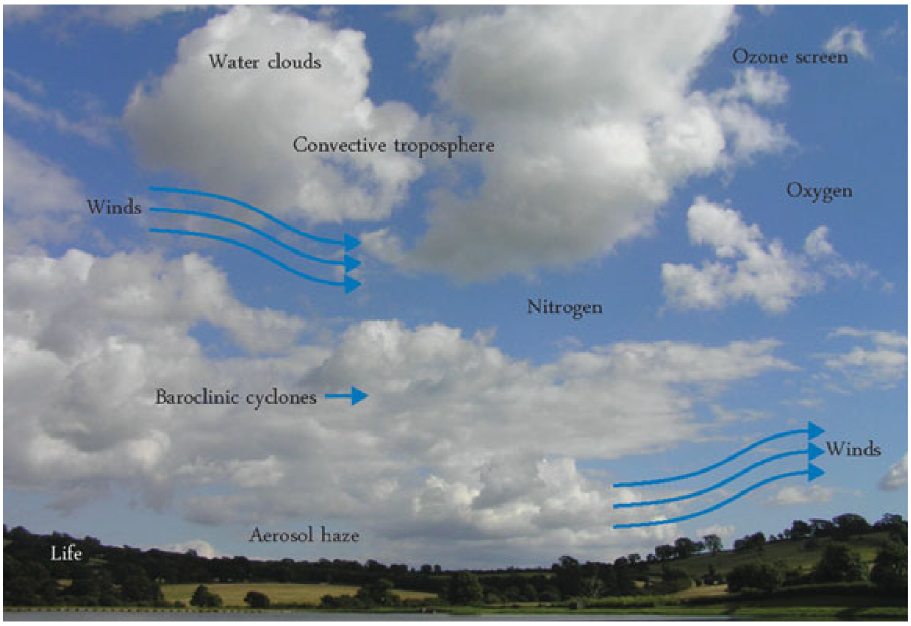
Epilogue

Now that we have crossed many eons of time and light-years of space, wandered in all corners of the periodic table, and experienced extremes of pressure and temperature, let us take another look at the Earth's atmosphere, one serene spring day in a temperate region.

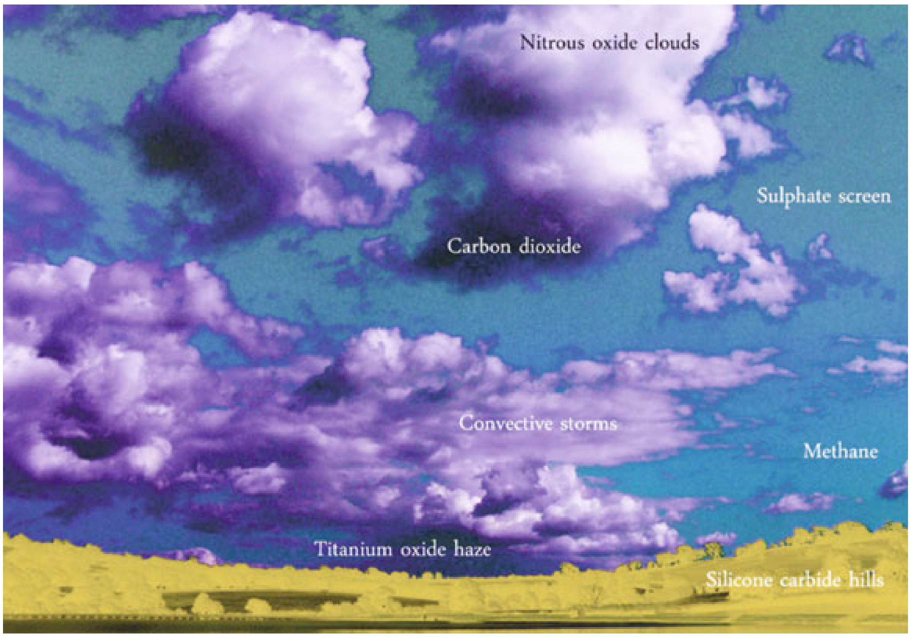
What do we see? A grand procession of clouds in a blue sky, some looking like animals, some making faces?

With our new "Alien Skies" glasses on, the landscape may look different.

We see a nitrogen atmosphere, with a huge fraction of reactive oxygen, and a layer of ozone overhead that blocks the incoming ultra-violet rays and prevents the clouds from rising into the stratosphere. Droplets of water form clouds, because vast atmospheric swirls, formed when thermal currents try and fail to move from Equator to Pole, mix warm air with colder air. A thin haze of aerosols – small particles of dust, sand, soot or ash: gives a reddish tinge to distant views. On the surface, an extraordinary green colour signals the ubiquity of photosynthetic life on this planet, explaining the continued presence of the free oxygen.



With our “Alien Skies” glasses, we realise how this atmosphere is one of so many possibilities: blue skies on some planets spell carbon dioxide; clouds can be made of methane; storms can be due to winds blowing from day side to night side; on a tidally locked planet the stratosphere can be heated by titanium oxide; the Sun can be green because of sodium atoms; the cliffs can be made of silicon carbide; the haze can be due to ruby dust. As for life on other planets, we still don’t have much of a clue ...



What are the limits? How alien can alien atmospheres be? Is there anybody to watch them? These are early days in the great voyage of discovery of planetary atmospheres.