Our Nature

The Earth As Home

William Leiss

A Cangrande Book

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Library and Archives Canada Cataloguing in Publication

Leiss, William 1939 –

Our Nature: the Earth as Home

"A Cangrande Book".

ISBN 978-0-9738283-6-8

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Cover Image

NASA: The Blue Marble Earth montage was created from photographs taken by the Visible/ Infrared Image Radiometer Suite (VIIRS) instrument on board the Suomi NPP satellite (30 January 2012): https://photojournal.jpl.nasa.gov/catalog/PIA18033

Contents

Note to the Reader:

This essay and its "Guide to Further Study" are intended for the general reader and for use in classroom settings at high schools, colleges, and universities. The contents seek to help students, citizens, and public officials, who are not experts in any of the fields of the natural sciences, to make up their minds on what to believe about the risk of global warming. This risk, as described by a large group of climate scientists, involves the possibility that very damaging events, such as dangerous rises in sea levels, may begin to happen all around the world well before the end of the present century. Climate scientists have calculated how likely it is that such events may happen and have told us that they have very high confidence in their conclusions. Now citizens and their governments must make a decision on whether or not to believe what is said by climate scientists about our possible future. Furthermore, if they conclude that belief in the scientists' case is warranted, citizens will then be responsible for supporting the goals of policies and regulatory instruments, along with their attendant costs, designed to prevent those damaging events from coming to pass.

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PREFACE

Eons of past time and ceaseless change, embedded in earth's geology and in the evolutionary biology of species, are the twin factors which provide the best guide to the major risks facing humanity in the present day. The current state of the planetary surface on which we all reside, as well as the many steps in the emergence of *homo sapiens* from its ancestral origins in the hominin tribe, are the results of specific stages during prior times and of new developments. The history of our planet is a 4.5–billion–year record of violent upheaval, driven by forces deep below its surface, such as volcanic eruptions and marked most dramatically by the push and pull of gigantic continental masses against each other. Its atmosphere too, as well as climatic conditions, have likewise been repeatedly altered, a function of the interaction between the earth's crust and external factors such as solar radiation, strikes of massive asteroids, the planet's orbit, the tilt of its axis, and others. Geologists have named the stages in this record: The current one is known as the Quaternary, which has featured the growth and decay of continental ice sheets in 100,000-year cycles. The most recent episode, beginning roughly about 12,000 years ago, is called the Holocene.

The human counterpart to the first phase of the Quaternary, known as the Pleistocene, was the migration of our hominin ancestors (such as *homo erectus*) out of their African homeland, which is thought to have begun as much as 1.8 million years ago. We ourselves have been baptized with the term "anatomically modern humans"; we originated in Africa between 300,000 and 250,000 years ago and began to disperse about 70,000 years ago. Because these later treks occurred in the most recent cold glacial cycle, climatic conditions were not conducive to rapid human population growth – until the arrival of the Holocene, the warm interglacial, when temperatures were about 6°C (11°F) warmer than they had been just 7,000 years earlier. And then, in the geologically-brief period of less than 10,000 years, the population of modern humans literally exploded, by which time wandering hunter–gatherers had become settled farmers and herders, and the first civilizations had been born.

The recent evolutionary success of *homo sapiens*, therefore, resulted wholly from the fortuitous confluence between the modern geological history of the planet's land surface, on the one hand, and the formation of a relatively new hominin species, equipped with a large brain and upright gait, prepared to exploit its new environmental opportunities, on the other.

And exploit them we did: Around 3000 BCE there were an estimated 45 million of us worldwide, and the number reached 1 billion for the first time around 1800 CE. But at that point most people were still living on primitive agricultural holdings, beset by backbreaking manual labor, impoverishment, and the endemic threat of famine and infectious disease. Then the Industrial Revolution marked another decisive turn, at least as dramatic as the one from hunter–gatherers to farmer–herders more than ten millennia earlier. Arguably, humans were thereby propelled into a new epoch, called the Anthropocene, where we have become so dominant on the planet that we are now influencing the future stages of global climate. And if this is the case, we humans collectively have become responsibile, for the first time in the evolution of our species, for the next stages in our climate history.

The scientific argument that human-caused factors are forcing the global climate along a new pathway – one that could bring great harms to human settlements around the turn of the next century – is contested by some who attack the theory and the evidence marshalled in order to support it. But that argument is also resisted by many others who point to the lack of full certainty in the scientists' predictions, or who refuse to accept the idea that humans could exert much influence on the climate, or who profess to believe that climate scientists are perpetrating a hoax on the public, or who aver that God will decide the outcome. Since 100% certainty is impossible to achieve in predictions of this kind, we are left with a throw of the dice: Does one accept the contentions of climate scientists or not? If it is expected to be costly to say yes, as it probably will be, then why not just wait and see what happens?

In the pages that follow I have tried to frame the debate over the credibility of climate science in a new way, by putting the issue in the double-perspective of the earth's geological history and the evolution of species, culminating in the fortunate nexus of the Holocene and modern humanity.

Introduction

What I refer to in this essay as “the modern world” or “modernity” is the historical epoch in Western Civilization which began in the late sixteenth century. The construction of the new path had been prepared sometime earlier by the Renaissance, a cultural transformation in European history that had been stimulated by a rediscovery of the intellectual achievements of Ancient Greece and Ancient Rome. The events that then transpired during the period of modernity took place in Europe and its environs, including North Africa and the Middle East as well as European Russia. Over the succeeding centuries those events transformed a world-view which until then had been dominated, since the early part of the Common Era, by the three Abrahamic monotheisms – Judaism, Christianity (in its two variants, Roman Catholic and Greek Orthodox), and Islam. Although the European “voyages of discovery” to the rest of the planet had already begun in earnest, the intellectual transformation I have in mind did not conquer the rest of the world until well into the twentieth century.

The vibrant core of this set of changes was the gradual replacement of a religiously-constructed concept of nature with a scientifically-based one. The single great figure who fully epitomizes this revolutionary change is of course Galileo Galilei (1564–1642): Preceded by the pathbreaking work of Nicolaus Copernicus, and contemporaneously with that of Johannes Kepler, Galileo made with his telescope the scientific discoveries that inaugurated the new science of nature. But he also generalized his astronomical findings in elaborate treatises that set two ways of thinking, old and new, in direct and open opposition to each other. So forceful was his juxtaposition of the two ways of thinking that he obliged the dominant institution of his era, the Church of Rome, to enter into open warfare with both his person and his theories. High officials of the Church labelled his theories “foolish and absurd” and placed his treatises on the Index of Prohibited Books; they hauled him in his old age before a tribunal of the Church’s Holy Office of the Inquisition, threatened him with torture, and condemned him to life imprisonment, a sentence later commuted to house arrest for the rest of his life.

Thereafter about two hundred years elapsed before the Church gave up its futile struggle against modern science, and by the time Darwin's theory of evolution appeared in 1860, all religious opposition to scientific theories had ceased to matter very much, with respect to the conduct of society as a whole, however bitterly it was expressed. This amounted to a fundamental transformation in Western Civilization: An epoch of history stretching back about thirteen centuries, dating from the political supremacy of Christianity achieved with the sudden conversion of the Emperor Constantine in 312 CE, was upended.

One of the key aspects of that earlier epoch had been a cosmological vision of our earthly home, known as the geocentric theory. The scientific revolution replaced that vision with a new one, the heliocentric theory, but at first nothing much changed so far as the sense of what it meant to live life on planet earth was concerned. However, the march of the new science was restless and relentless, and the first transition was followed by others, between the seventeenth and the twentieth centuries, which eventually painted a wholly different picture of the earth as the site of our home in the universe. These discoveries are charted in the sections that follow; in each there is a brief account of the particular scientific discoveries that, taken together, were responsible for the changed portrait. All of them were gradually assimilated into popular culture as well as into a radically-new technological and industrial apparatus which marked a profound break with the material conditions of life known to all earlier times.

The series of sections to follow illustrates one basic truth, namely, that the modern conception of earth as our home rests entirely on observations, evidence and reasoning contributed by the new chemical, physical, astronomical, geological, and biological sciences. These sections seek to illustrate the many ways in which those sciences have discovered that the universe and the earthly home we inhabit are not what they seem to be when observed with the naked eye. Beneath the surface of what we see with our ordinary senses, there is a vast domain of *hidden regularities*, which would become known as the "laws of the universe," both on the macroscopic scale (countless numbers of stars and galaxies) and the microscopic scale (atomic and subatomic structures). As a result, we can understand virtually nothing about the reality of the world around us if we rely only on our unaided senses. Religion too had told a story about a hidden, unseen reality, one made up of spirits – souls, angels, and demons. But the story told by the modern sciences was of a different kind altogether, because it relies on the systematic collection of evidence, rigorous deduction, and experimental proof. Moreover, the sciences have changed the story's details continuously, over centuries of time, always by building on prior achievements. The details change, but the *method of inquiry* remains essentially the same: It is the method that Galileo described at the beginning of the seventeenth century.

Over the long course of events since the late sixteenth century, modern science drove humans out of the Garden of Eden, that cloistered domain designed specifically for them, overseen by a punitive deity, which presented a caricature of the reality of nature. Science ushered them outside and into a landscape suffused with the light of reason but devoid of any inherent meaning. Another way of putting this thought is to say the neither the universe as a whole, nor our home planet, was *made for us*, contrary to what had been asserted by the religious version of the geocentric theory. In other words, the immense span of the universe now described by science is neither a welcoming nor a secure home for creatures like us. (On the other hand, we have *adapted* ourselves rather nicely to the limiting conditions of the planet's current geological state, known as the Holocene.)

Therefore, humanity would find it necessary to create a different narrative to explain its existence in the context of a universe that is as a whole hostile to biological life of any kind whatsoever. This narrative has been crafted by the modern sciences of nature – astronomy, physics, chemistry, geology, and biology. In a sense, humans in the age of modernity would have no option but to put their trust in the new sciences of nature, for the simple reason that there is no credible alternative story. We are obliged to believe that these sciences, these complex and barely comprehensible products of humanity's own innate reasoning powers, telling a story far different from the religious one we had been used to, were valid and indeed unchallengeable. For most of us, with our very limited understanding of the basic scientific concepts, a pragmatic proof suffices: Our lifestyles are entirely dependent on an elaborate suite of technologies, which by and large do useful work for us, and we simply cannot doubt that the invention of these technologies originates with the modern sciences of nature.

These technologies have thoroughly transformed the material conditions of everyday life. This overabundant cornucopia comes with a price, namely, that we, the beneficiaries, must put our trust wholly in science's new story and find in it a satisfactory basis for the meaningfulness of existence. To help persuade the rest of us that we could indeed live with this new story, philosophers assured us that in manipulating nature for our benefit scientists had everything under control. Then the bubble burst. Suddenly people were informed that they could no longer continue along down the well-worn path toward material prosperity prepared by the exploitation of fossil-fuel energy sources; and moreover, that if nations refused to heed this message, there would be truly catastrophic results, most likely beginning in about a century hence, for future generations. It is perhaps unsurprising that this news was not well-received, especially in still-developing nations that had expected to follow the path to prosperity originally laid out in the West. The news was not even welcomed among nations already having been made rich by such means, where many of their citizens hoped to become far richer still. Many political leaders in both groups of countries sensed the popular mood. They decided to ignore the message, because, they said, the dire forecasts just were not and could not be credible.

In response the scientific community doubled down on its predictions, becoming ever more specific about our needing to avoid some fast-approaching thresholds beyond which the onset of serious harms would be unavoidable. They were saying, in effect, that events in the natural world were in danger of spinning out of our control and that, once human-induced climate warming passed those thresholds, very likely there would be no turning back. Having been schooled for so long in the doctrine that the modern nexus of the sciences, technology and industry was unstoppable, many were unwilling to accept the idea that humanity was in the process of being pushed back into the old circumstances where everyone was at the mercy of natural forces. At present, many of the world's citizens believe that the scientists delivering this unwelcome message must be just wrong, or if not, that new technologies will soon fix things and thus there is no need to change established ways. In the following sections we will trace the long trajectory of modern science and ask if these are reasonable positions to take.

ONE: GEOCENTRIC HOME

Figure 1: Two Angels turning the Axes of the World (14th Century)

With the spherical earth at its center fixed and unmoving and the sun and planets circling faithfully around it, with the stars mounted in place as the top half of a moving sphere, serving as a brightly-lit celestial canopy, something like a covered stadium over which the roof rotates 360 degrees, the age-old geocentric model of our universe appealed to both theological orthodoxy and plain common sense (since the earth does not appear to move). Geocentrism or the geocentric model was first an idea originating in Ancient Greece; the earliest known source is a treatise by Anaximander from the 6th century BCE, but it was also featured in the better-known works of Plato and Aristotle two centuries later. It was standardized for the next millennium by Claudius Ptolemaeus (Ptolemy) in the 2nd century CE, who was obliged to add elaborate mechanisms in order to explain all of the observed motions of the planets.

The Ptolemaic version of geocentrism became the standard cosmological model in the West for the next 1500 years. Our home was presented in it at the very center of things for the simple reason that in Judaeo–Christian thought the universe had been expressly made *for us*, for us humans, by a benevolent but also a rather demanding deity, in the creation story told in the *Book of Genesis*. Since the universe was made for us by God, who is perfection personified, its structure and operation were thought to be unchanging for all time. It was designed to be the unalterable stage-set or backdrop against which the only meaningful drama in the life of humanity was played out, namely, the struggle against one's natural inclinations and Satan's temptations in order to try in vain to obey God's commandments. Set in stark juxtaposition to the tangible reality of life on earth were anticipations of the only two other imaginary places that mattered: Hell, the dreaded site of eternal punishment, overseen by Lucifer at the center of the earth; and Heaven, site of hoped-for eternal reward, placed with God at the outer limits of the universe, beyond the stars.

TWO: HELIOCENTRIC HOME

Heliocentrism – the theory that the earth and other planets revolve around the sun in a "solar system" – was first proposed by Aristarchus of Samos in the 3rd century BCE. But it was then forgotten again for almost two millennia, in part because his works did not survive intact. The astonishing Polish genius Nicolaus Copernicus revived it early in the sixteenth century, using some mathematical calculations made by Islamic scholars a few centuries earlier.

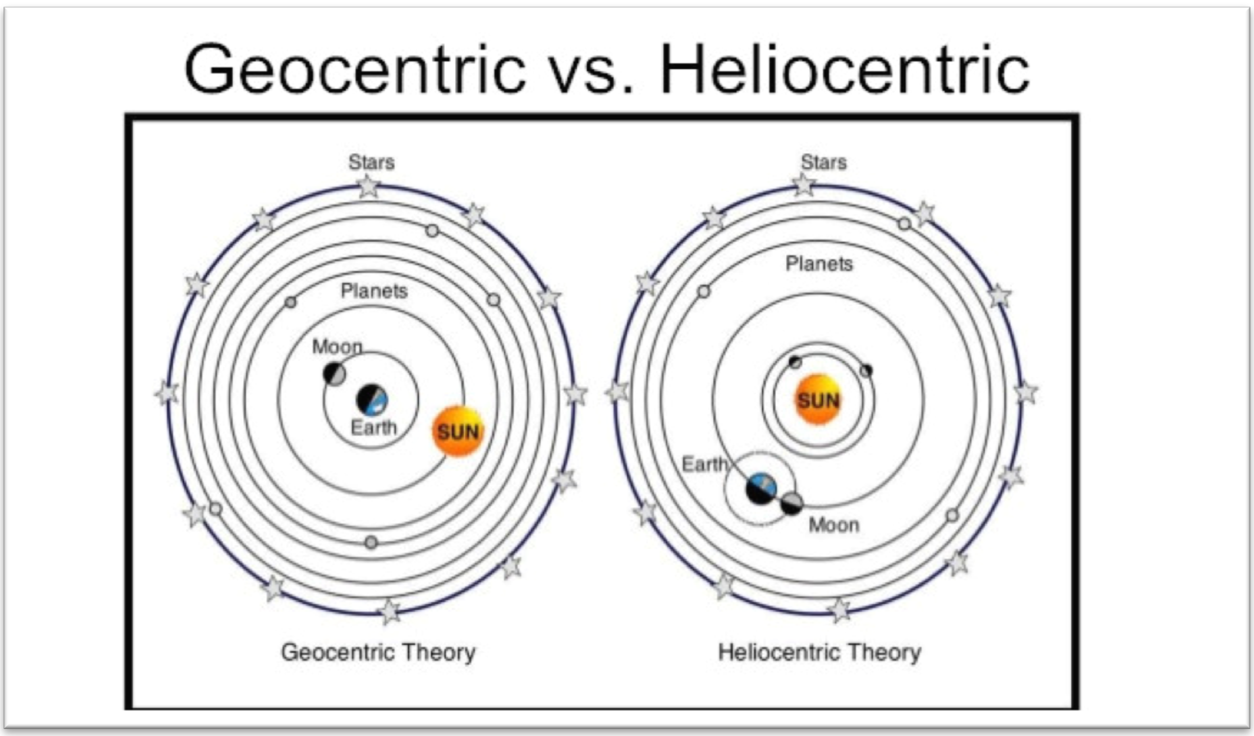


Figure 2: The Two Earth-Systems

Putting the sun at the center of our solar system, with the earth and planets revolving around it, does not seem – at least from the perspective of the present day – to be such a momentous affair, and many might have wondered why the Christian churches, both Catholic and Protestant, made such a fuss about it for so long. To us today the new astronomy based on heliocentrism would appear to have no readily-apparent and significant implications for either everyday life or the religious faith of ordinary people.

The sixteenth-century Church of Rome disagreed. The remarkable philosopher and mystic Giordano Bruno had opined that our sun was just one of innumerable stars in the universe, for which (along with many other doctrinal faults) he was tried for heresy before a group of senior cardinals, hung upside down naked, and burned alive at the stake in Rome's Campo di' Fiori in 1600. But some fifty years after Galileo's later torments heliocentrism received powerful support in 1687 in Isaac Newton's great work, *Mathematical Principles of Natural Philosophy*. His cosmology made a radical break with the science of his time: Whereas Kepler's earlier "laws of planetary motion" referenced only our solar system, Newton's three laws sought to describe *motion as such*; that is, wherever matter exists in the universe there is a hidden regularity, one that can be expressed in part in an astonishingly simple form, in the "iconic" equation for the second law, $F = ma$ (force equals mass times acceleration). Astute viewers of *2001, A Space Odyssey* will recognize the first law, inertia, in the scene where Hal pushes the human astronaut working outside the space capsule into distant space, but they might not readily grasp the universality of the act.

By the late eighteenth century, observations using more powerful telescopes by William Herschel (the discoverer of Uranus) and others were definitively showing that there were far more stars and other heavenly bodies than had been earlier assumed, and thus that neither our sun nor our solar system could represent the center of the universe. In the early twentieth century the ground-breaking discoveries made at California's Mount Wilson Observatory by Edwin Hubble revealed that there were countless galaxies beyond the Milky Way and that the universe was not static but rather both vast and expanding.

THREE: COSMIC / GEOLOGICAL HOME

Figure 3: NASA Hubble Space Telescope: "The Pillars of Creation" (7,000 Light-Years Away)

In the unimaginably large universe we inhabit, time is distance and vice-versa: The further out into space we gaze with our newest arrays of radio and optical telescopes, the further back in time we see. Even this apparently simple proposition is actually hard for most of us to understand, but some can detect its plain implication: There is in a sense no passage of time in the universe. Our telescopes now detect light which originated almost as far back in time as the Big Bang (which occurred about 14 billion years ago) – although the source of that light is now something like 46 billion light-years away from us, since the universe has been expanding. Some idea of the scale of the universe is given by the following dimensions:

Macroscopic Scale:

Size of the Universe (diameter): 93 billion light-years;
Speed of light: 299,792,458 meters per second;
Distance light travels in one year: ~9.5 billion km.;
Conceptional Composition of the Universe: 4% visible matter, 22% dark matter, 76% dark energy (what the latter two actually are is unknown);
Physical composition of the Universe: dust, gas, stars (and a relatively few planets);
Average Temperature of the Universe: 2.7Kelvin (2.7 degrees above absolute zero);
Age of the Universe: 13.77±0.059 billion years;
Size of the supermassive black hole at the center of the Milky Way galaxy: Equivalent to the mass of 4.1 million times that of our sun;
Age of the Earth: 4.55 billion years;
Length of time life has existed on earth: 3.5–4 billion years;
Number of minutes in a year: 526,000.

These are scales that are literally incomprehensible for most of we humans who amble about the surface of our planet at a walking speed of something like 5kmh (3mph) during today's average life expectancy of somewhere between 50 and 75 years. The strange reality of the physical composition of the universe as a whole has no real meaning for our lives.

Where exactly are we, sitting as we do on humble planet earth, in all this vastness of space? Our home solar system resides in the Milky Way, a barred spiral galaxy 100,000 light-years wide having two main arms; our planet and solar system is located on one of its minor arms, called the Orion Spur, about 25,000 light-years away from the galaxy's center. Each galaxy in the universe contains billions of stars like our own sun: Our Milky Way is a large galaxy, containing perhaps 300 billion of them. The Milky Way forms part of the so-called

Local Group, which includes the much larger Andromeda Galaxy, one trillion stars in size. The Andromeda Galaxy, now some 2.5 million light-years away, will collide and merge with the Milky Way in about 4.5 billion years – but this should not be a cause for undue concern, since our earth will be gone by then, having been roasted to a crisp by our expanding sun.

Figure 4: The Andromeda Galaxy (NASA 2018)

In the universe as a whole there may be as many as 2 trillion galaxies, and something like 10^{22} to 10^{24} (10 million billion billion) stars. Calling our little planet just an insignificant speck of dust within the whole box of visible matter would be to greatly exaggerate its relative size.

Casting our minds back to the Geocentric Model and the Biblical Creation Story, one would naturally want to ask why any deity would have gone to the trouble of fashioning so large a setting for our benefit, but monotheistic gods do not tolerate questions. A reasonable speculation on this issue might conclude that the point was to show just how insignificant our lives are in the grand scheme of things. But are we also alone? Scientists are now doing a survey of possibly habitable exoplanets, where the probability of finding life is dependent in the first instance on the "circumstellar habitable zone," the distance of a planet relative to its sun which is just right for its atmosphere to exert enough pressure to sustain liquid water. There may be billions of such possibly life-sustaining planets in the universe. But before we get our hopes up about meeting some of their inhabitants, it would be wise to ponder a calculation made by an astrophysicist in a 2014 book entitled *Our Mathematical Universe*, suggesting that "only a thousandth of a trillionth of a trillionth of our Universe lies within a kilometer of a planetary surface." Biological life may be fairly considered to be the rarest phenomenon in the entire universe, and it will be rarer still when all of our planet's surface is turned into a metallic crust by our expanding sun, on its inevitable evolution toward becoming a red dwarf, some billions of years hence.

Notwithstanding the findings of astrophysicists, the modern geological sciences have busied themselves with figuring out what materials were used to fashion our modest home. It was not until the eighteenth century that science broke decisively with the Biblical accounts of earth's origins and with the corresponding theological calculations on the age of the universe, which had dated creation to about 4000 BCE. During the nineteenth century scientists began to argue that the age of the earth must be reckoned in the millions of years. Theorizing that the earth was originally just a huge blob of heaving, molten rock, in 1862 the Englishman William Thomson calculated that it would require somewhere between 20 million and 400 million years for the earth's surface to have cooled into its present state. From then until now, new techniques such as radiocarbon dating have pushed back that estimate to 4.55 billion years.

This is not a story of peaceful change, but rather one of extraordinarily violent activity, driven by the stores of residual heat in the earth's mantle. The most visible manifestations of this violence are, of course, volcanic eruptions and earthquakes, which are now understood as a function of plate tectonics: The earth's crust is composed of a collection of vast platforms on which the continents and the oceans sit, which grind against each other, pulling apart and pushing against their boundaries. This knowledge of the earth's composition is a splendid twentieth-century achievement based on the use of seismic waves, whose shape and speed as they propagate through the planet provide clues to what lies below our feet.

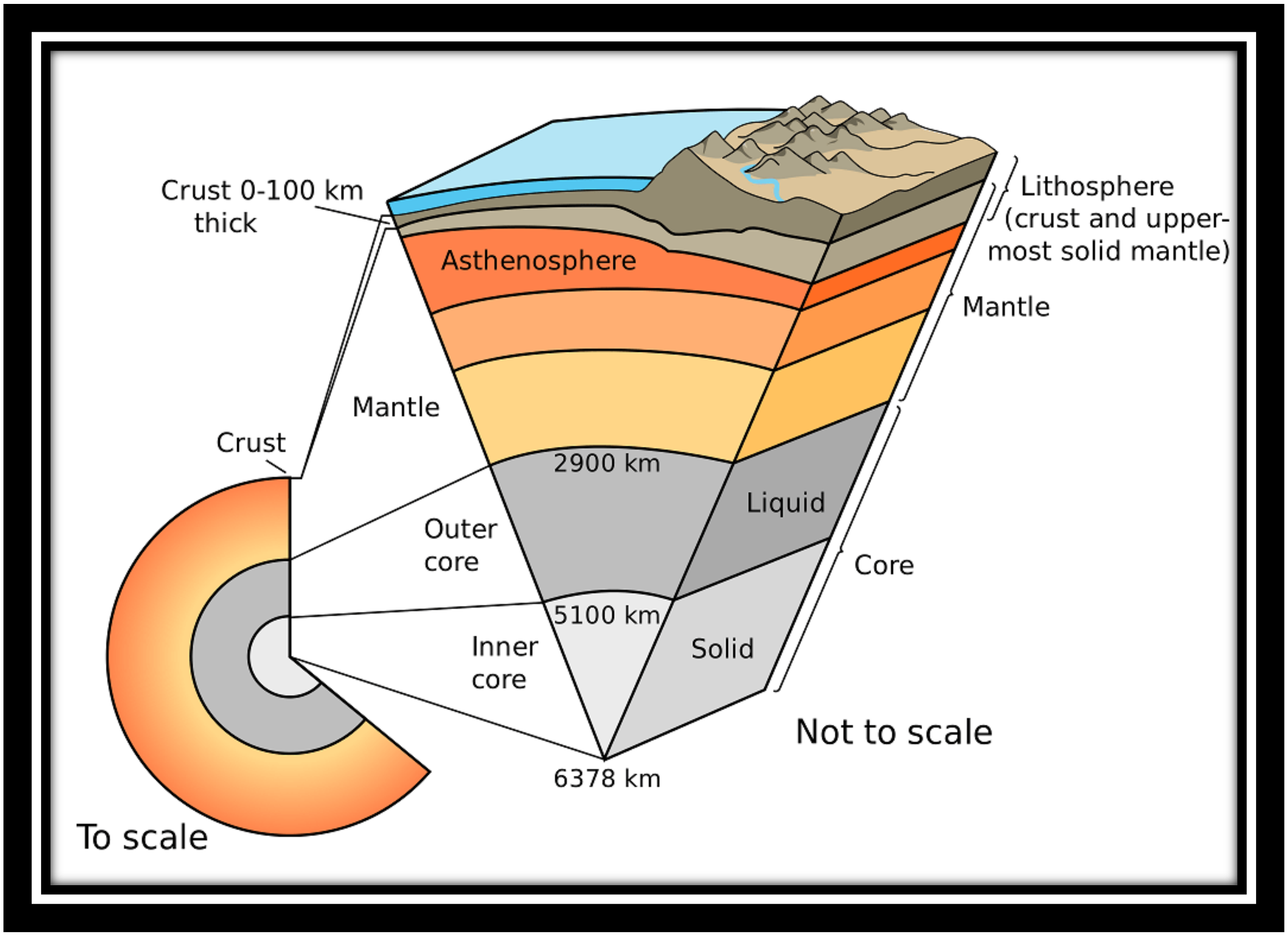


Figure 5: Geological Strata of the Earth

The key to life on earth is the fact that the planet has retained very large amounts of liquid water on its surface, almost certainly beginning with its original formation. The most direct impact of the planet's composition on biological life is its effect on the atmosphere, which is held in place by gravity and stratified into layers from densest near the surface to the thinnest, the exosphere, the boundary between the atmosphere and outer space. In the earth's earliest history, the atmosphere's first composition was mostly hydrogen gases such as ammonia and methane. The second phase, beginning about 4 billion years ago, occurring during the heavy bombardment of earth by huge asteroids, was made up of nitrogen and carbon dioxide. This gave rise to the carbon cycle, and this phase also includes what is known as the Great Oxygenation Event, starting some 2.45 billion years ago. One or two "snowball earth" episodes, during which the earth was almost totally covered in ice, occurred some 750 to 550 million years ago (MYA(, the second of which lasted 100 million years – but which, happily, was followed by the "Cambrian Explosion," a huge expansion of animal and plant life-forms.

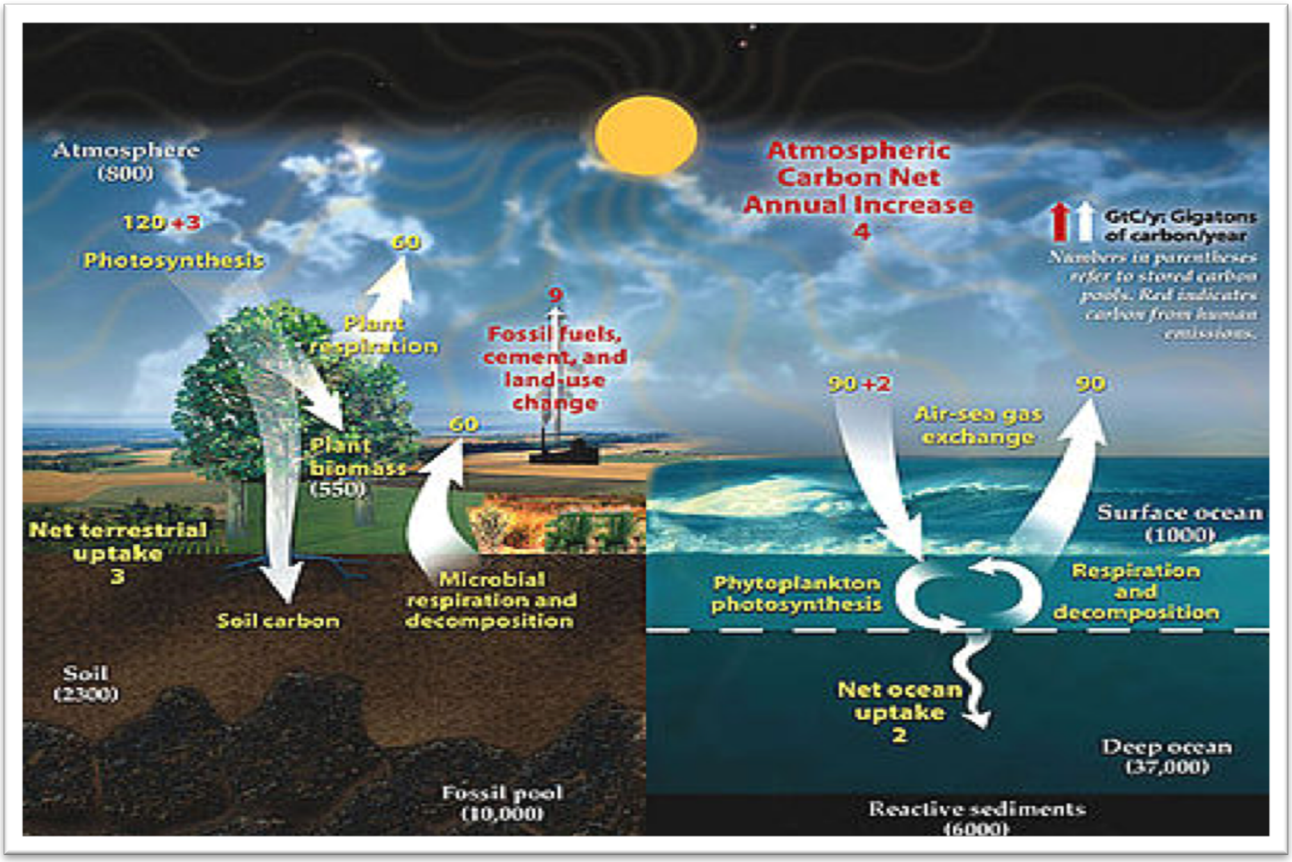
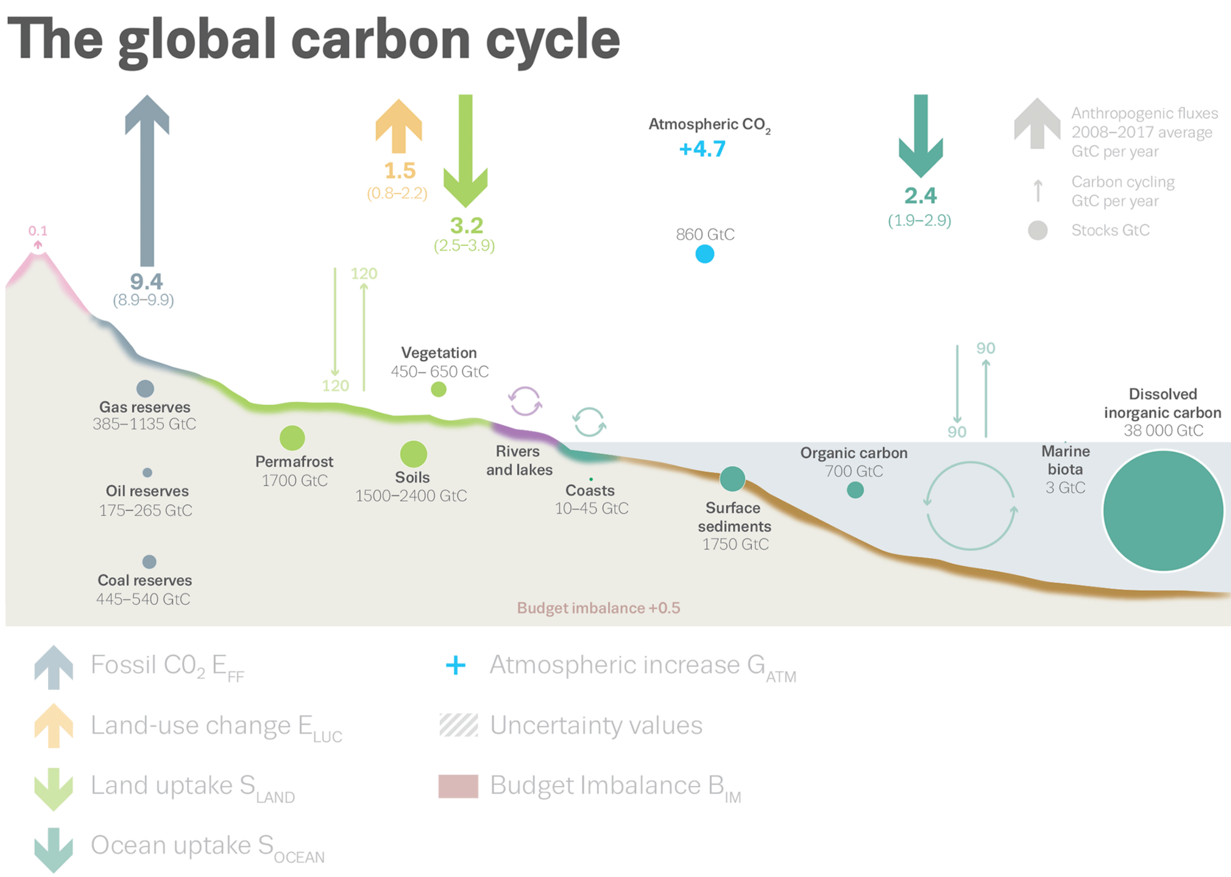


Figure 6: The Carbon Cycle



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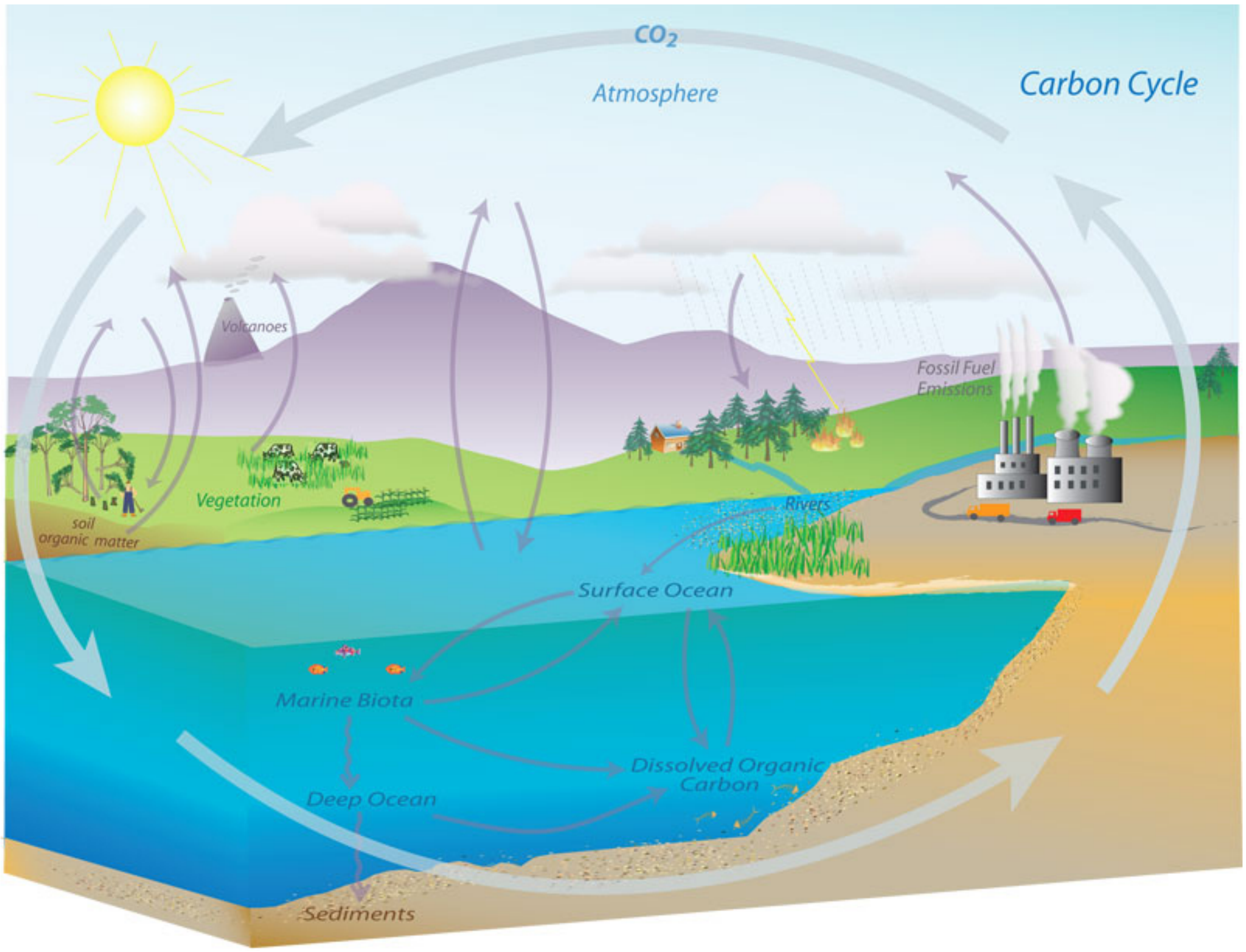

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Carbon is stored throughout a vast network of reservoirs – atmosphere, terrestrial biosphere, sediments, oceans, and the mantle and crust – and recycles among all of them. The emergence of the carbon cycle was the fundamental step in the origin of life, since carbon is the main constituent of all biological compounds. Fluctuations in the composition of the atmosphere during more recent times, including our own, have often been associated with major volcanic eruptions, revealing the essential relationship between the geology of earth's crust and the lower levels of its atmosphere. The mix of atmospheric gases now is about 78% nitrogen, 21% oxygen, and 1% trace gases, including argon, neon, helium, as well as carbon dioxide and others, known as the greenhouse gases. The average temperature at the earth's surface was much warmer in the distant past than it is now, reaching +8°C (+14.4°F) relative to the present some 55 MYA and steadily declining since then to -6°C (-11°F) below present levels some 20,000 years ago before rising again to the current level.

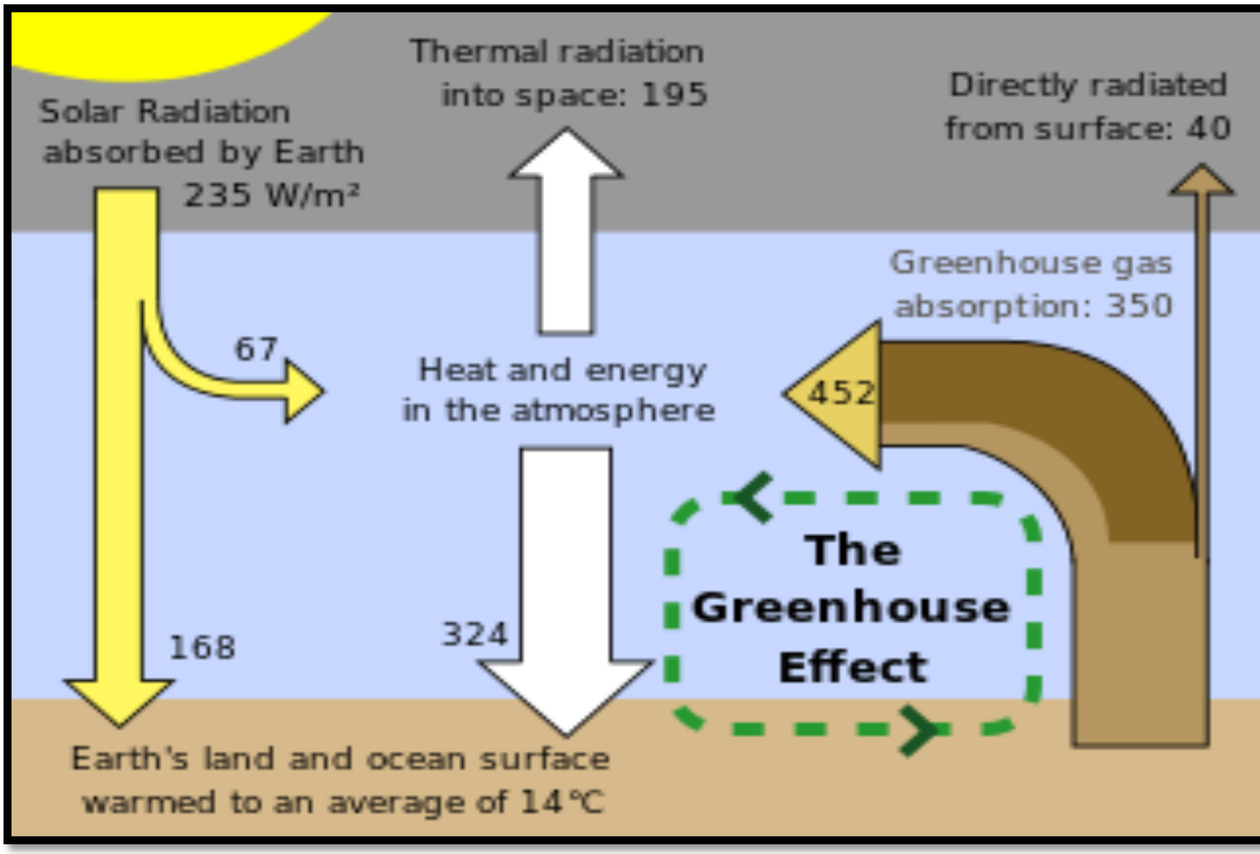
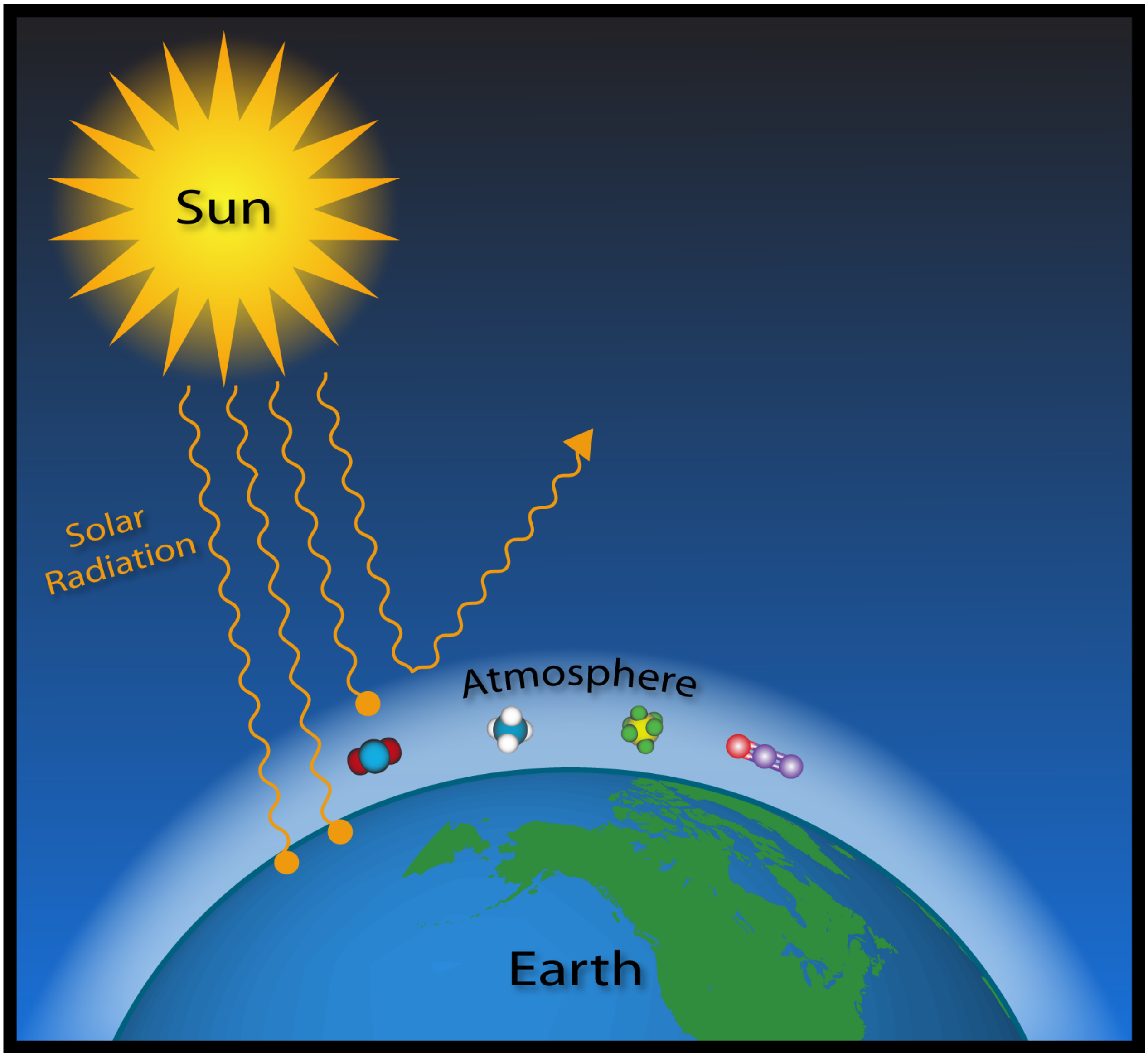


Figure 7: The Greenhouse Effect



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The fact that the earth's average surface temperature at present is about 14°C (57°F) is due to the greenhouse effect, without which the temperature would be -18°C (-0.4°F). Earth's surface is warmed by absorbing radiation from the sun, some of which is reflected off the surface (especially by glaciers and sea ice) and is reradiated back into space; however, some of the reflected energy is trapped and held by a small suite of gases in the atmosphere, notably water vapor, carbon dioxide, ozone, and methane. The effect is not visible to us; we first knew of it due to the work of some nineteenth-century scientists (Joseph Fourier, Claude Pouillet, John Tyndall, and Svante Arrhenius).

FOUR: EVOLUTIONARY HOME

In terms of its impact on the popular imagination, Darwin's theory of evolution dwarfs any other scientific discovery in modern times. Species did not suddenly appear on earth in final form and remain unchanging thereafter, the theory claimed, but rather were never-finished products of a long chain of being stretching back over billions of years to the beginning of life on earth, and to an entity known as the "last universal common ancestor." The process which governs those changes is natural selection, the interaction of a species with its environment which itself is always being altered by geological mechanisms. Successful adaptations survive and flourish, whereas less-successful ones disappear.

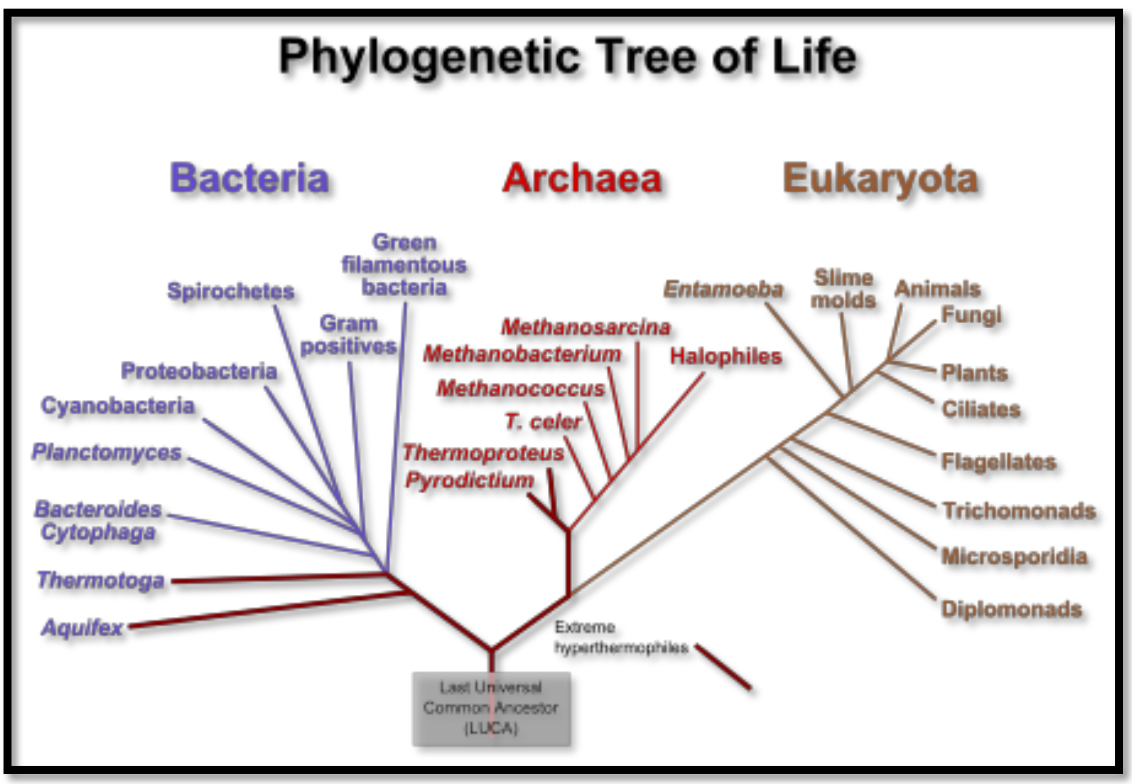

Figure 8: The Tree of Life

Perhaps the most radical thought of all in this new theory was that the process of change is both spontaneous and largely random: Adaptations which arise randomly in the continuous reshuffling of DNA in the living representative of all species may or may not encounter the environmental conditions that make it possible for any specific adaptations to take hold and persist in succeeding generations. For a long time – indeed, down to recent times – some persons simply could not believe that an organ as complex as the eye, for example, could possible have evolved in this fashion, and on the contrary must have been designed and instantiated by an intelligent deity. But the dominant view has held firm: Given a long-enough time, countless numbers of spontaneous mutations, and a favorable set of environmental conditions, even so complex a biological organ as the human brain is known to be the end-product of the gradual formation of its constituent parts in a long evolutionary line stretching back to the origins of mammals (220 MYA) and vertebrates (505 MYA).

Changing environmental conditions introduced an element of pure chance into the mix at a macroscopic level. Scientists specializing in the new fields known as paleobiology and geobiology have documented the following five events, known as "mass extinctions," in earth's geological history:

End Ordovician, 444 million years ago (MYA), 86% of species lost;
Late Devonian, 375 MYA, 75% lost;
End Permian, 251 MYA, 96% lost;
End Triassic, 200 MYA, 80% lost;
End Cretaceous (Cretaceous–Paleogene boundary), 66 MYA, 76% lost.

The "End Permian," occurring at the boundary between the Permian and Triassic periods, is the one known colloquially as "the great dying." The "End Cretaceous" event was triggered by the impact of a massive asteroid striking the earth, leaving the Chicxulub Crater beneath Mexico's Yucatan Peninsula; whereas it was deadly for most the extant species at that time, notably the dinosaurs, it was also likely responsible for the fact that the entire groupings of our own direct ancestors, hominids and hominins, and therefore we too, exist at all: Before the extinction of the non-avian dinosaurs, the top predators of their time, the only extant mammals were very small and likely to stay that way. Some scientists believe that a sixth episode of this type – referred to as the Holocene extinction – may be already under way. This one is the result of human activity, and may have begun with the extinction of megafauna such as the woolly mammoth at the end of the last Ice Age. But the threat of extinction facing large numbers of mammals on all six of our planet's settled continents has accelerated rapidly during the twentieth century and into the twenty-first.

Archaic humans – *homo erectus* and then *homo heidelbergensis* – began dispersing out of Africa as much as 2 million years ago; the latter, which flourished about 500,000 years ago, was the probable ancestor of our relatives, the Denisovans and Neanderthals. Anatomically modern humans arose in Africa as much as 300,000 years ago and began leaving some 70,000 years ago, first heading East to Asia and Oceania, then to Europe about 40,000 years ago. Our own species (*homo* sapiens), along with our Neanderthal and Denisovan cousins, endured and then began to flourish throughout the last three in a series of glacial–interglacial cycles, each lasting about100,000 years; during the last Ice Age, humans occupied parts of northern Eurasia as the continental glaciers waxed and waned.

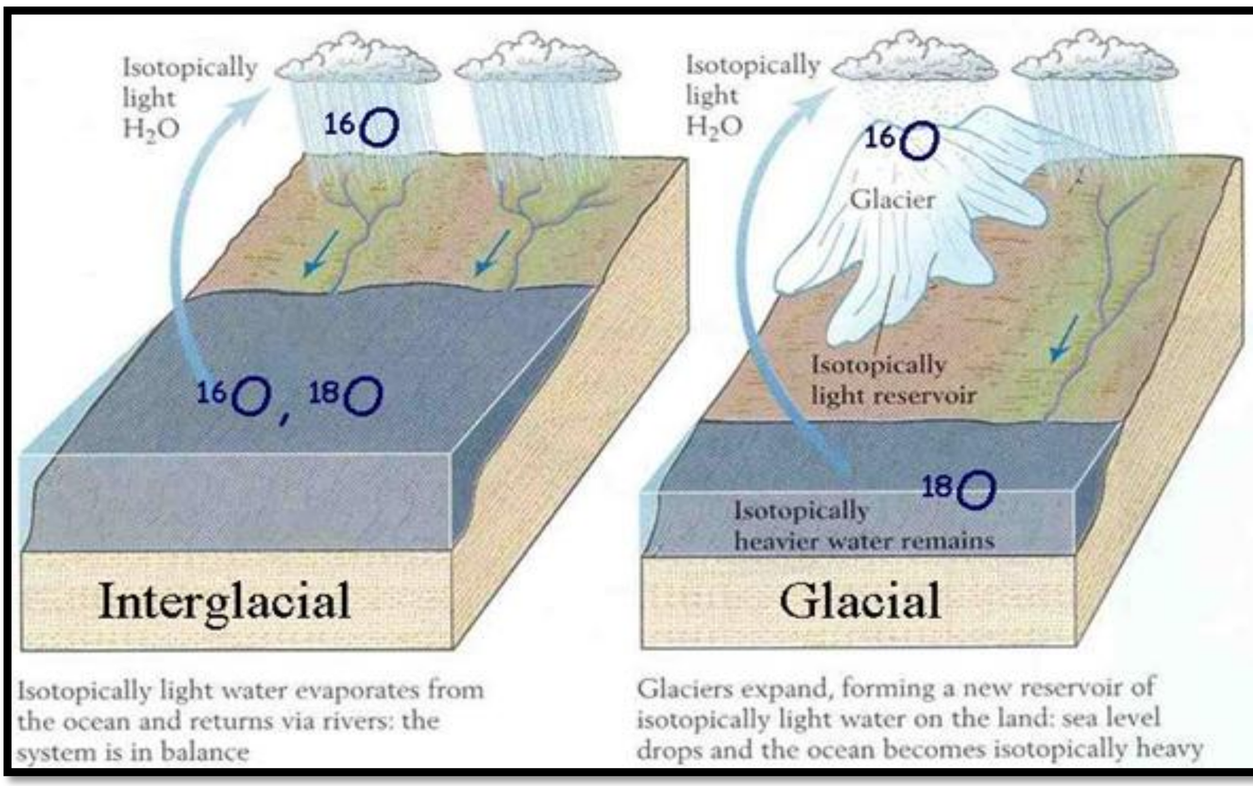

Figure 9: The Glacial - Interglacial Cycle

The large asteroid which hit the earth 65 million years ago, as well as the group of massive volcanic eruptions that followed, set in motion the last in the earlier series of mass extinctions of extant species, and the fate of one of them (the non-avian dinosaurs) was a necessary step in the evolution of larger mammals. The brutal truth is that evolutionary processes in biological life on earth offer no guarantees about ultimate outcomes for any particular species. In other words, there was no guarantee that a class of mammals would have appeared at all, no guarantee that large mammals would have emerged within that class, no guarantee that the primate order would have arisen, no guarantee that either hominid or hominin species would have evolve out of the primates, and finally, no guarantee that anatomically-modern *homo sapiens* would appear in Africa, having arisen by chance out of its hominin ancestors.

There have been long periods in the planet's more distant past when its surface conditions would have been uninhabitable for creatures like us, and other times when its changing atmospheric and geological attributes proved lethal for vast numbers of existing species. The detailed knowledge about the history of the earth's atmosphere and geology, acquired by scientists over the course of the past two centuries, shows beyond the shadow of a doubt that the dynamic relationship between the makeup of our planetary home, on the one hand, and the capacity of all species (including our own) to arise and flourish, on the other, is a very tenuous one indeed.

This tenuous relationship is illustrated well by what happened during and after the period known as Last Glacial Maximum (LGM), occurring between 27,000 to 19,000 years ago, which was marked by a severe cooling of the climate and the expansion of the continental ice sheets. Anatomically modern humans were already well-settled in Europe at the onset of that period, but this population suffered a serious decline as a result of the climatic change and was forced to retreat to the southernmost areas of Europe. There was some significant climate instability just before the LGM, and this may well have been a factor in the extinction of our cousins, the Neanderthals. Following the LGM there was a repeated shifting between shorter-term warming and cooling phases, as the climate system was in the process of transitioning from the last glacial to the latest interglacial. (In this context "shorter-term" means periods of one to a few thousand years. The transition from the glacial to the interglacial may be likened to attempting to start an engine that has been sitting idle for a very long time: On the initial tries the engine turns over but fails to catch.) Around 14,500 years ago, during the rapid onset of one of the severe cooling episodes, the existing human population in Europe was basically wiped out, thereafter to be replaced later, when temperatures rose again, by a distinctively-different group; the evidence for this process relies on mitochondrial DNA retrieved from fossil remains.

If there are lessons for the present day to be learned from this period of time in our relatively recent past, we appear to be reluctant to draw them. The plain truth of the matter is that the planetary geology and biology which defines the natural world in which our species has so far flourished is not of our making and we do not now, nor can we ever, control it. Since leaving behind the ancient conception of nature that suffused the theologically-based geocentric idea, we have come to believe that – to recall the idea attributed to the seventeenth-century philosophers Francis Bacon and René Descartes – we have become the "masters and possessors of nature." The time may soon come when we realize just how vain and preposterous such a notion is and has always been.

FIVE: CHEMICAL HOME

Modern chemistry begins with Robert Boyle in the seventeenth century but is most closely associated with the great Antoine-Laurent de Lavoisier (1743–1794), whose life tragically was cut short by his unjust execution during the French Revolution. The mid-nineteenth-century saw the decisive development, namely, the application of chemistry in the new Industrial Revolution, which gradually transformed every aspect of economic and social life. This is of course a long story, but it can be told in simplified form by referring to a single set of innovations, the Haber–Bosch process for producing synthetic nitrogen and ammonia.

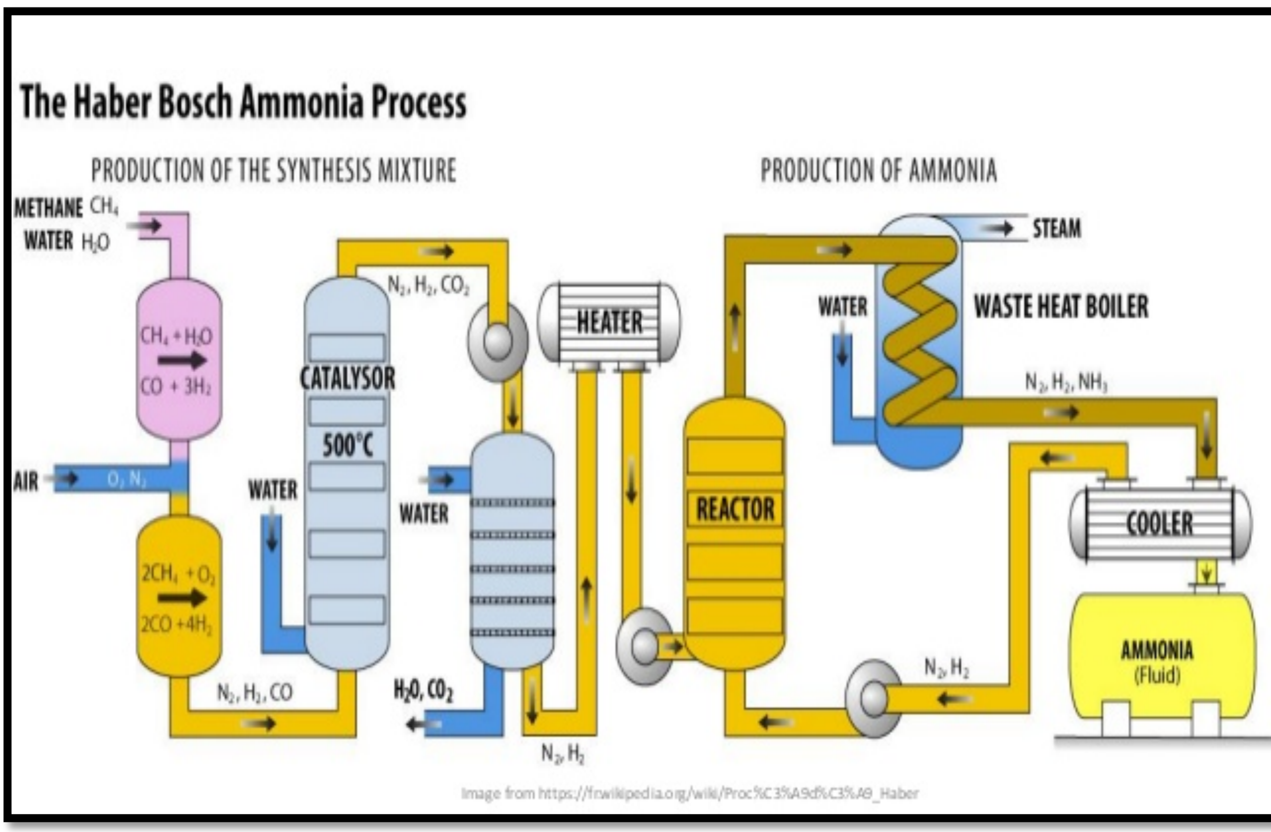

Figure 10: The Haber – Bosch Process

Nitrogen is by far the most abundant element in the atmosphere, but it is present there in its inorganic form which plants cannot use. Plants cannot fix inorganic nitrogen gas (N_2) from the air but rather assimilate organic nitrogen from the soil in the form of ammonium (NH_4^+) and nitrate (NO_3^-). Nitrogen in its organic form is an essential element in plant productivity: In traditional agriculture farmers to seek to raise the productivity of crops by adding organic nitrogen-rich substances as fertilizer, notably animal and human wastes. Guano – the accumulated excrement from seabirds and bats – has been used as a soil amendment by the Andean peoples of South America for centuries, since it is a rich source of nitrogen, potassium, and phosphate. During the early 19th century it was discovered by Alexander von Humboldt, a German naturalist and geographer, and was soon mined and formed the basis of an extensive international trade in Europe and North America, but its global supply is limited and could not meet the rapidly-expanding desire for intensive farming.

In 1909 the German chemist Fritz Haber developed at laboratory scale the process, named for him, in which atmospheric nitrogen (N_2) is converted into ammonia (NH_3) by a reaction with hydrogen (H_2). The company BASF purchased the rights to it and Carl Bosch succeeded a decade later in scaling up the process to produce huge industrial quantities of ammonia, which was used to make artificial fertilizer. (Unfortunately, it also produced an abundance of high-explosive material used in artillery shells and bombs in World War I and thereafter.) It is estimated that the increased food supply generated by this single astonishing innovation is responsible for the existence of up to 50% of the world's current population. It symbolized the overall impact from the application of chemistry to industry in completely transforming the material basis of human life, including novel materials (plastics), medicines, and energy. The disciplines of chemistry and chemical engineering are as a whole the sciences upon which we depend most directly for the lifestyle we enjoy. These sciences manipulate the structure and properties within an entirely hidden realm of atomic elements and compounds, which operate inside our own bodies as well as in the surrounding environment, in order to bless us with lives that are longer, healthier, and more comfortable than anything which could have been imagined by our distant ancestors.

SIX: RADIOACTIVE AND QUANTUM HOME

The great German physicist Max Planck told the story of consulting one of his academic advisors in 1874 about which field of science he should choose to study, whereupon he was strongly discouraged from going into physics, on the grounds that this field was pretty much complete and that there were no important discoveries remaining to be made. He ignored this well-meaning advice, and the events which transpired during his long lifetime amounted to nothing short of a revolution in the human understanding of the physical world. This is of course a long story and only the barest outline is told here.

The first stunning breakthrough, in the 1890s, was radioactivity, the recognition that atoms were not indivisible and that certain forms of matter spontaneously emit energy from nuclear decay in the form of invisible rays. This was initially the work of William Roentgen (x-rays), followed by Henri Becquerel and of course Marie and Pierre Curie, in their investigations of uranium and thorium and the discovery of radium and polonium. The logical conclusion was that matter and energy were not two entirely dissimilar things, but were somehow bound up with each other. Next came Einstein's 1905 paper on mass-energy equivalence, which generalized the idea of the convertibility of mass and energy and first suggested (in a formula that only much later was expressed in its now-familiar form, $E=mc^2$) what a vast amount of energy was bound up in matter and might be released from matter under certain conditions. It took another 30 years before these two fundamental ideas – radioactivity and mass-energy equivalence – were brought together in the experiments by Otto Hahn and Lise Meitner which demonstrated that atomic fission could be induced in the laboratory. Soon the German-Jewish refugee physicist Leo Szilárd realized that, if the splitting of an atom could be *controlled* in a reactor, its energy might be released upon demand. After another few years the first atomic bomb had been created.

The second breakthrough was quantum theory. Max Planck was there at the beginning in his 1901 study of black-body radiation, which is thermal electromagnetic radiation emitted and absorbed by all matter at an infrared wavelength, thus not visible to the human eye. He discovered a law that was then built on by Einstein in 1905 in his concept of the photoelectric effect, which determined that the transmission of light occurred in discrete packets of energy called photons. The new field in theoretical physics was called quantum theory and later quantum mechanics or quantum electrodynamics. Those who made early contributions to it included Max Planck, Werner Heisenberg, Albert Einstein, Max Born, and Erwin Schrödinger, every one of them a German, the last three of whom were among many others of Jewish origin who were forced to flee for their lives when the Nazis came to power in 1933.

As mentioned, the rise of the new physics was stimulated especially by the discovery of electromagnetic radiation at the end of the previous century, and it deals exclusively with the behaviors of matter and energy largely at the atomic and subatomic levels – thus with a set of phenomena all of which are below the threshold of our unaided experience of the world. These behaviors are decidedly odd, and extremely difficult for most of us to comprehend.

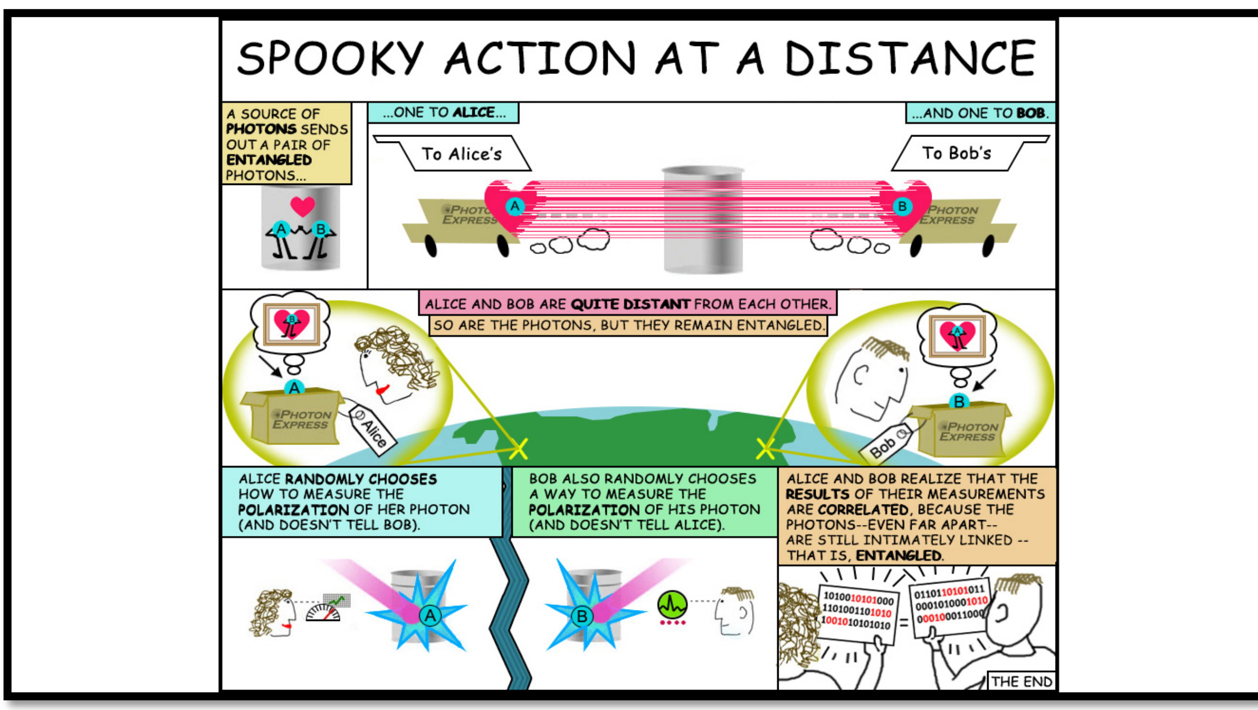

Figure 11: "Entanglement" of Elementary Particles

The mathematical notation and equations through which scientists explore this dimension of reality are simply impossible for most of us to fathom, when considered from the standpoint of our ordinary understanding of matter and energy. And yet quantum–mechanical theory has repeatedly been experimentally confirmed over the course of almost a century, including recent experiments at the University of Vienna on entanglement (Gibney 2017). But that is not the important fact about them so far as the story being told here is concerned. What is supremely important is the simple observation that in quantum mechanics the nature we think we all know disappears completely.

Our fundamental experience of nature is defined by such criteria as the evident solidity of matter, gravity, the warmth of the sun's rays and the weather, the passage of time, and the visible phenomena conveyed by our senses – motion, light, sound, smells, touch and feel, taste. Subatomic physics tells us that none of this (except gravity) is *real*. Most of us do understand as a result, say, of taking high-school chemistry classes, that for example some of the materials we deal with, on an everyday basis, are not the ultimate reality but rather may be decomposed into their underlying constituents. We know from high-school health studies that our bodies depend on the conversion of food into energy as well as the intake of substances we cannot see with the naked eye, such as minerals and vitamins. We know that doses of radiation can cure some cancers, even if we don't know exactly how this happens, and that antibiotics can kill bacteria, although we cannot see the life-forms that are making us ill. And so on. We know that in times past every one of these experiences in everyday life had a single explanation: God's will.

But beyond this level of understanding of the world around us, most of us are simply clueless. In their search for the ultimate level of nature's reality, physicists currently describe things that can only be observed as ghostly traces on the outputs of detectors used in the huge machines known as particle colliders, some of which decay into something else within time-frames so fleetingly short as to be inexpressible in ordinary language. When we try to add up the key characteristics of the dimensions of nature's reality on the small scale, presented to us by the field of particle physics, we get something like the following randomly-selected list:

Microscopic Scale:

Planck length (unit of length): 1.616229(38) $\times 10^{-35}$ meters:
(10^{-35} = 1/100,000,000,000,000,000,000,000,000,000,000,000);

Duration for a subatomic process: one yoctosecond (one trillion-trillionth of a second (10^{-24}: 1/1,000,000,000,000,000,000,000,000), the unit of time for emission of a gluon from a quark;

Mass of the constituents of an atom: Proton (composed of three quarks held together by gluons): $1.6726231 \times 10^{-27}$ kg;

Mass of the constituents of an atom: Electron ($9.1093897 \times 10^{-31}$ kg);

Mass of the constituents of matter: Neutrino (much less than one-billionth of the mass of a proton).

Perhaps the most remarkable fact of all in these numbers is that they are so exact. To visualize just how small a particle the neutrino is, note that countless trillions of them pass through the entire earth (with its solid iron core) each second, without striking anything, except extremely rarely. For reality in the quantum dimension is mostly just an empty space in which electromagnetic forces play.

What is one to make of all this? These are dimensions, on the microscopic scale as well as on the macroscopic scale reviewed earlier, that bear no relation whatsoever to the time and space in which we live. The bottom line is, the vast majority of us simply will never be able to understand the reality of the nature out of which we have been made.

SEVEN: A MODELLED HOME

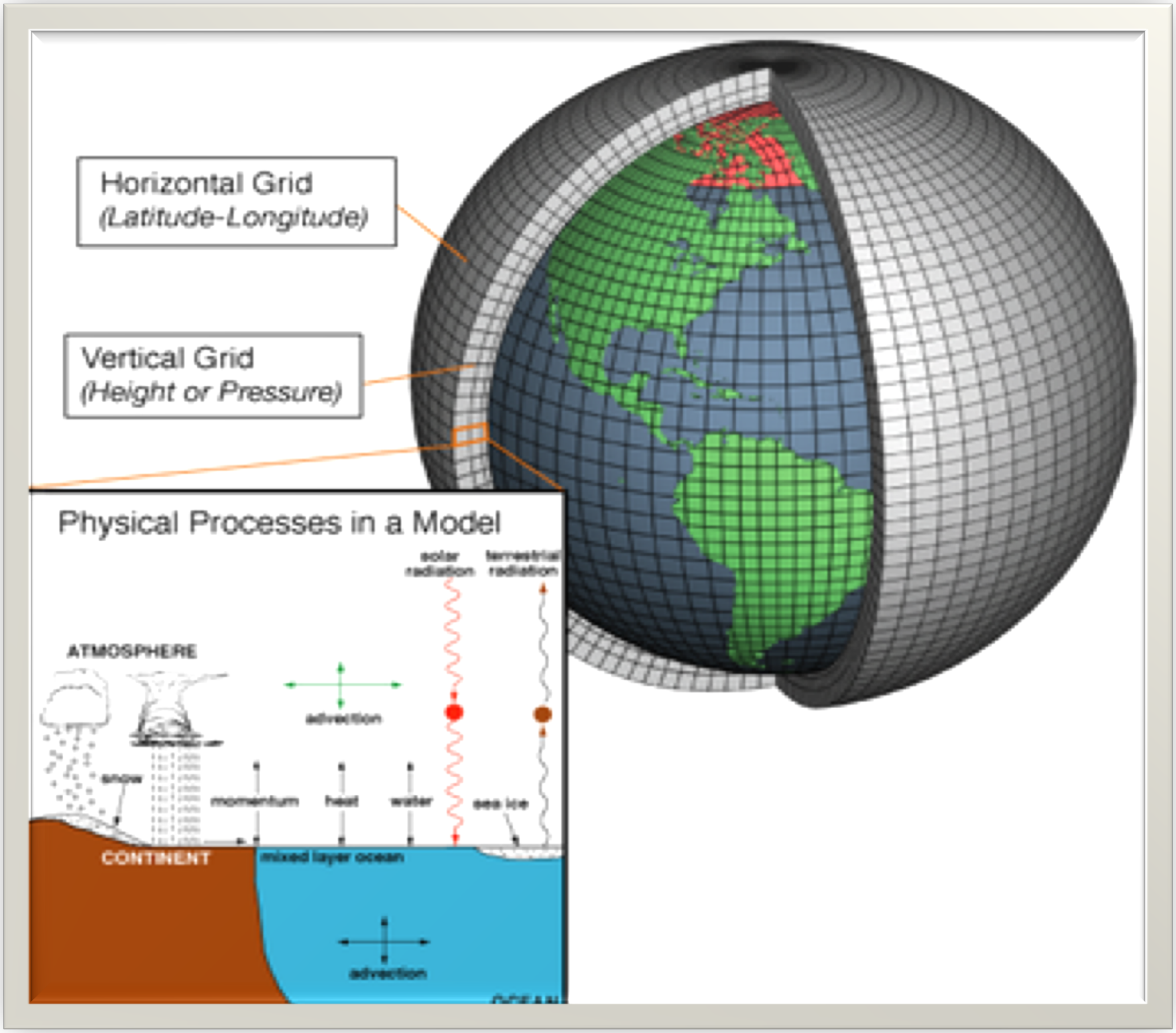

Figure 12: Coupled General Circulation Model (CGCM)

Coupled General Circulation Models have two subcomponents, one for the atmosphere and another for the oceans. Each of them is a four-dimensional model, consisting of three spatial dimensions plus time. The spatial dimensions form a grid, akin to sets of boxes piled above and below each other, one set for the earth's surface, one for the oceans, and one for the atmosphere. The atmospheric grid may have as many as 20 vertical layers and the oceanic, 30. Enormous amounts of data generated by the whole set of boxes are inputted into the model, which is why running the model requires the use of the largest supercomputers available. The data include measurement of such factors as water vapor, solar radiation, wind, clouds, ocean circulation, albedo (reflectivity off ice and snow), heat, atmospheric gases, and others. The great complexity of the models is made necessary because all of the three spatial components (land surface, atmosphere, and oceans) continuously interact with each other, as do some of the separate factors, which means that all the positive and negative feedback loops among them must be described and measured. The CGCMs use equations drawn from the principles of physics, notably thermodynamics and fluid dynamics, to specify how these interactions occur. Results from running such models are designed to give as accurate a picture as possible of how and why the earth's climate changes over time. The results are simulations, that is, re-enactments or imitations of the complex natural processes which, scientists believe, actually give rise to the climatic events we experience in real life.

CGCMs, then, are extraordinarily complex constructions made up of interacting large-scale processes (such as the hydrological cycle and the carbon cycle), huge data sets of many different kinds, and analytical methods drawn from physics and chemistry. In order to validate the results that they generate, scientists input current data and run the models backwards in time, to see if they can reproduce the known climate and weather conditions of the past. They seek to fine-tune their models by varying certain parameters and rerunning them again and again. When they are satisfied that the model's predictions of past events are as close to what actually occurred as they can achieve, they run the models forward in time to make predictions about what is likely to happen in the future. The results are probabilities, that is, estimates of how likely it is that specific events will happen, and their objective is to achieve high confidence in those predictions. They spend a good deal of time describing the uncertainties that remain, which are inevitable in this type of work, and which prevent them from claiming they are certain that the predicted outcomes will indeed occur.

Their most significant general finding is that over the course of the twentieth century anthropogenic (human-caused) changes are the main reason that global temperatures appear to be rising relentlessly. There are a number of such changes, such as land-use practices, but by far the most important is the release of increasing amounts of greenhouse gases, especially carbon dioxide and methane, as a result of human activity, where the burning of fossil fuels stands out as a decisive factor. In this regard scientists emphasize the concepts of climate forcing and climate sensitivity, that is, the extent to which the earth's global average temperature changes in response to increases in the emissions of greenhouse gases. Beginning in the late 1980s groups of climate scientists have advised governments and their citizens to institute policies that would rein in the emissions of these gases, primarily by moving away from generating energy by fossil-fuel use and mandating the use of alternative sources of energy such as solar and wind power.

Eight: The Earth We Now Inhabit

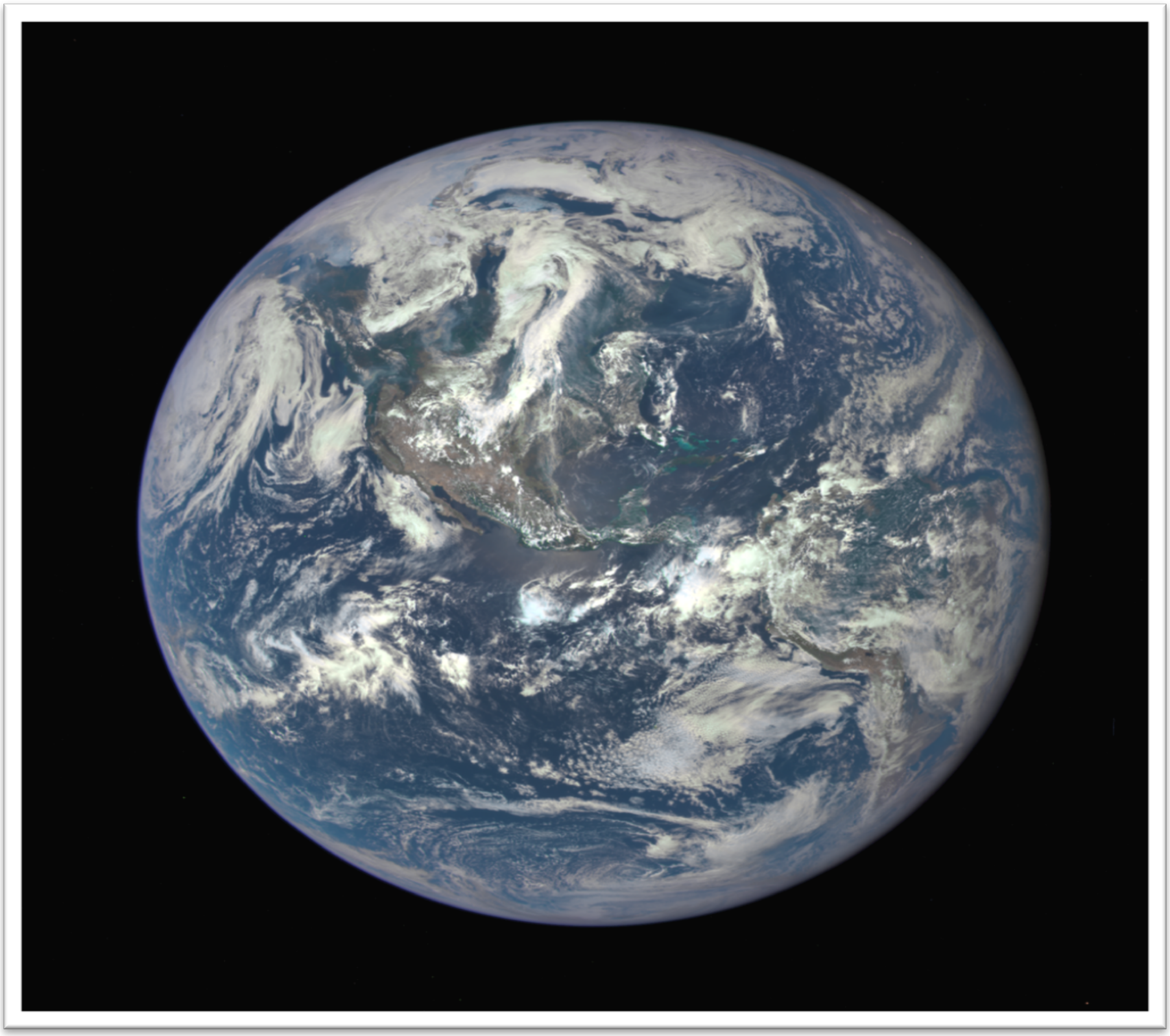

Figure 13: NASA Image of Planet Earth

We modern humans evolved during the period known as the Quaternary, which runs from about 2.6 million years ago to the present, the most distinctive feature of which – occurring over the last 1.2 million years – is a set of cycles of glacial and interglacial periods amounting together to about 100,000 years each, divided approximately into 80,000 colder and 20,000 warmer years respectively. The mechanism responsible for this feature is known as the Milankovitch Cycle, and it results from variations in our planet's tilt on its axis and its orbit around the sun, both of which affect the amount of solar radiation striking the planet's surface. In this cycle the glaciation occurs in the Northern Hemisphere, and during the most recent Glacial Maximum the ice reached as far south as 40° latitude (about where Chicago and New York City are now located) and was as much as 4 kilometers thick. Two contemporary scientific discoveries are especially important in this context. The first is the radiocarbon dating of fossil remains: Anatomically-modern humans (*homo sapiens*) are now thought to be up to 300,000 years old; therefore, our species evolved within the Late Quaternary, and most successfully in the Holocene, which began 11,700 years ago. The second innovation is the drilling and extraction of ice cores from the massive East Antarctic Ice Sheet, which descends to a depth of almost 5,000 meters, from which data can be extracted to provide a detailed picture of global temperature changes for the past 800,000 years. Scientists can reconstruct the planet's climate history for this period because the ice cores contain visibly distinct layers of trapped carbon dioxide gas and other material.

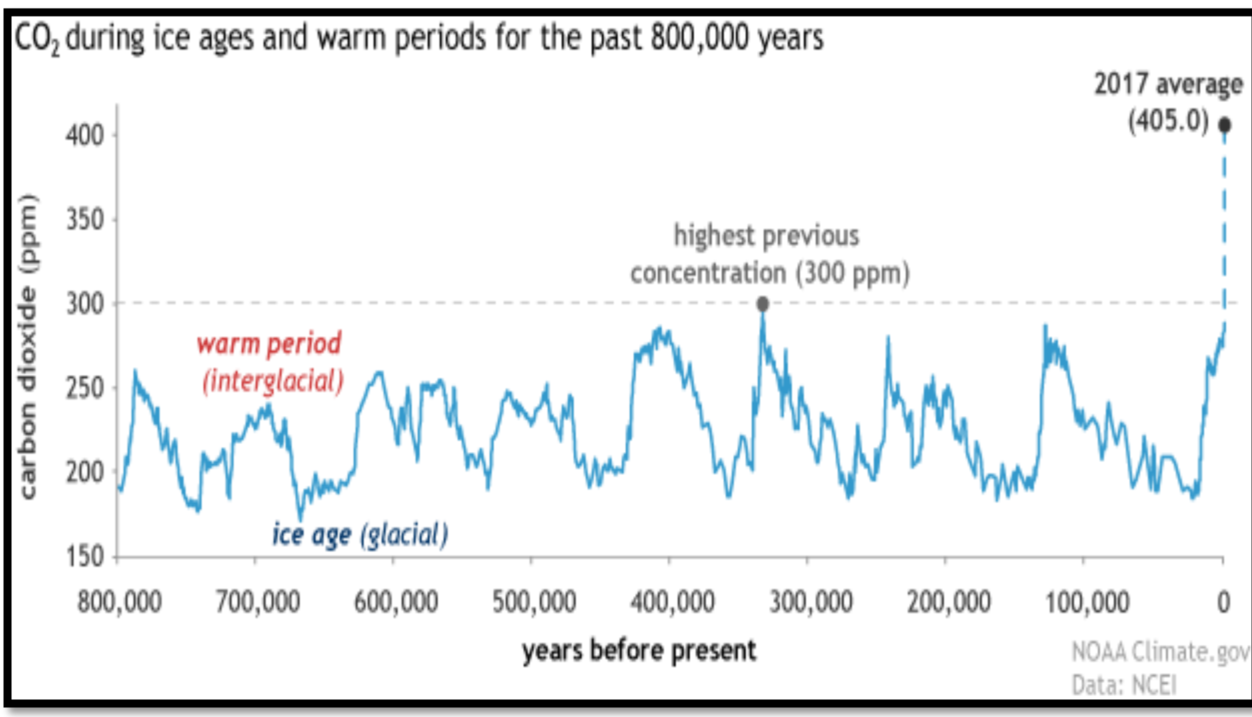

Figure 14: Graph from the Vostok Ice Core for the past 800,000 Years

The East Antarctic ice-core results present a picture of the temperature and CO_2 record across eight glacial–interglacial cycles. For dating dealing specifically with the Holocene (covering only the most recent 11,700 years) there is a trend line of rising global temperatures following the Late Glacial Maximum, when around 20,000 years ago the temperature was 6°C (11°F) colder than it is now. But there were also significant intermittent episodes of cooling, especially in the period called the Younger Dryas (10,000–8,500 years ago); two notable “cold events” during this period are linked to large pulses of fresh water into the North Atlantic from the melting Laurentide ice sheet, disrupting the oceanic heat transport from the equator to the poles. Greenland ice cores, which provide the most precise data for the Holocene, show that there has been a remarkable degree of climate stability beginning about 8,000 years ago and lasting until relatively recently.

Domestication of plants and animals in agriculture and grazing is thought to have begun 12,000 years ago, just before the onset of the Holocene, and one estimate puts total human population at 2 million around 10,000 BCE. Following the Younger Dryas, shorter and less severe cooling cycles alternated with warming ones: 5000–3000 BCE, the Holocene Maximum, with temperatures 1-2 degrees Celsius (1.8–3.6 degrees Fahrenheit) above the current level, when ancient civilizations flourished in Egypt and elsewhere – and the human population had risen to 45 million – followed by a cooling trend for the next millennium, then shorter warming and cooling cycles down to the present.

At the beginning of the Common Era total human numbers are estimated to have been 170 million. During what is known colloquially as the “Little Ice Age,” a long cooling period lasting from about 1300 to 1850, global average temperatures decreased about 1°C (1.8°F) from the level reached in the Medieval Warm Period. During the early stages in this period human population growth ceased or declined somewhat, as a result of such events as the Great Famine and the Black Death in Europe in the early 14th century, but the overall trend line for the human population for the last two millennia has been relentlessly upward, reaching the milestone of 1 billion for the first time around 1800, leading to exponential growth in the twentieth century; at the end of 2018, the total stood at 7.7 billion.

In 2000 the chemist Paul J. Crutzen, who had won a Nobel Prize for his contribution to the ozone depletion issue, popularized the term "Anthropocene," referring to it as period – dating from the onset of the Industrial Revolution – during which our species had become so dominant on the planet as to be responsible for a transition to a new geological epoch. In this new epoch the major threats to other life-forms at present, caused by habitat destruction and other factors, involve loss of biodiversity, sharp declines in the population of wild land animals and amphibians, destruction of rainforests and forests, and oceanic acidification. Recent scientific estimates about the magnitude of the accumulated human impacts on the biosphere, expressed in terms of biomass, are: (1) of all mammals now on earth, 60% are livestock, 36% are humans, and 4% are wild; (2) chickens and other poultry are 70% of all birds, the remaining 30% are wild; (3) since the beginning of human civilization, 83% of wild land mammals and 80% of marine mammals have disappeared. The threat posed by global warming is discussed in the following two sections.

The sum total of all human impacts on the environment has been called our species' "ecological footprint." Our total demands placed on the store of natural capital (stock of resources) can be assessed with respect to the criterion of s*ustainability*: Taking both main types of resources, renewable and non-renewable, into account, how likely is it that our current level of demands for the population that exists now, and for possible further human population increases, can be satisfied from both the planet's regenerative biocapacity and its stock of depleting stores? And for how long into the future? (To be sure, the intensity of average *per capita* demands varies widely across the spectrum of richer and poorer nations.) A consolidated image of the ecological footprint is presented in the idea that at present "1.7 earths" are necessary in order to satisfy total human demands placed on our planet's environmental resources. This means that our present level of demands exceeds the earth's capacity to satisfy them sustainably, that is, indefinitely into the future, and that we are drawing down the accumulated natural capital of the earth – its bioproductivity and stock of non-renewable resources.

This image also leads to the question as to whether all of these accumulating human impacts may result in what is known as an "ecological collapse," involving a sharp and perhaps sudden reduction in existing biological productivity across the planet as a whole, constraining its carrying capacity for all extant species. Major events of this time are known from the geological past, especially the mass extinctions previously listed, which were caused by events such as violent and prolonged volcanic eruptions, large asteroid impacts, and sudden climate change.

Recently other scientists have been exploring the concept of "planetary boundaries," a set of nine parameters designed to measure the resilience of the earth's chief biogeophysical systems that sustain human life under present conditions. Their analysis starts with the following observation (Steffen *et al.* 2015): "The relatively stable, 11,700-yearlong Holocene epoch is the only state of the ES [Earth System] that we know for certain can support contemporary human societies." Then they ask whether the Holocene earth-system can persist in the face of current human pressures against it, as assessed by measurements in nine dimensions: atmospheric aerosol loading, altered biogeochemical cycles, biosphere integrity, climate change, freshwater use, land-system change, novel entities, ocean acidification, and stratospheric ozone depletion. They regard two of the nine (biosphere integrity and climate change) as "core" or critically-important processes. They find that in a total of four of these nine (biogeochemical cycles, biosphere integrity, climate change, and land-system change) – a set which includes both of the core dimensions – human perturbations may already be pushing the earth-system beyond the boundary zone, the point where it becomes uncertain whether the earth-system that now sustains us can persist.

NINE: HOTHOUSE EARTH

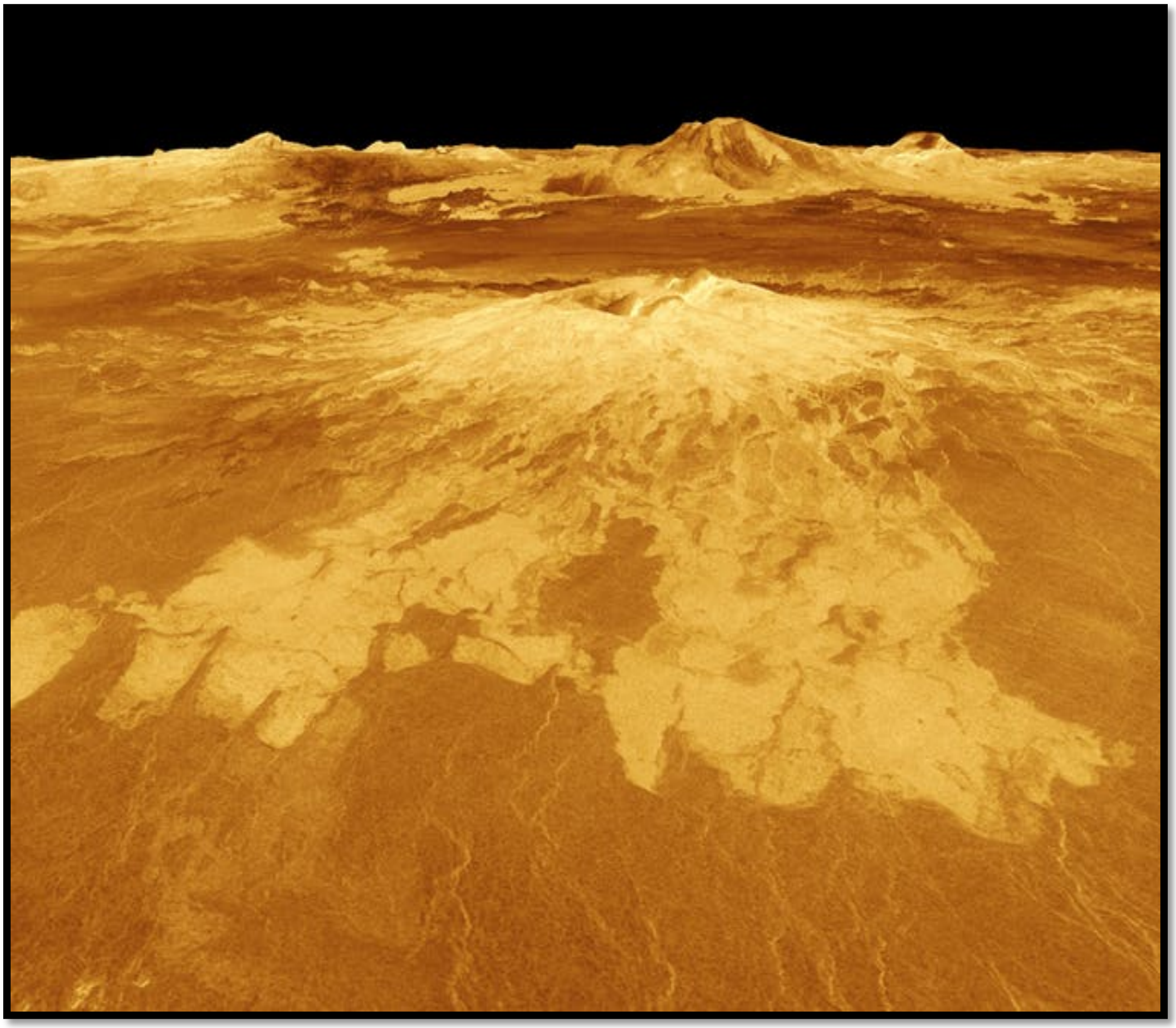

Figure 15: The Lifeless Surface of Venus resulting from a Runaway Greenhouse Effect (NASA)

Like the end-states that emerge from the operations in all very large and complex systems, both natural and human-constructed, the future trajectory of the earth's climate cannot be not easily diverted. In this respect the climate system is rather like human societies themselves, which for the most part respond to new information and changed environmental conditions slowly at best, and often not at all. As we have seen, scientists want to know how the earth's temperature will respond over the longer term to an increase in the loading of greenhouse gases in the atmosphere. They know that other factors will influence this response, in a set of both positive and negative feedback loops: water vapor, clouds, and sea ice, for example.

The parameter that interests them most is an expected doubling of the concentration of greenhouse gases in the atmosphere since the onset of the Industrial Revolution (with its greatly enlarged use of fossil fuels) in the late 18th century. But in trying to predict *when* the climate will respond to this specific input, they run into the problem known as *thermal inertia*: Even if new inputs, representing human-caused emissions of these gases, were somehow to be halted at once and completely, considerable time would elapse before the climate system eventually reached a new equilibrium level in response to this change. Thermal inertia is related to what is called the "atmospheric residence time" of various gases, which is the amount of time during which a gas continues to react to solar radiation, trapping energy and causing the atmosphere to heat up as a result. Levels of carbon dioxide are the most decisive input in this process; its mean residence time is about one hundred years. In simplistic terms this means that, were we to decide at some point to try to stop the earth's temperature from continuing to rise by reducing inputs of anthropogenic greenhouse-gas (GHG) emissions, the positive initial impact of our decision, a halt in rising temperature, would not be registered in the atmosphere until many decades thereafter.

In this context climate scientists started to refer to "thresholds" in the global warming scenarios, for two reasons, among others: (1) thermal inertia, as described; (2) the risk that, after a certain amount of warming had been induced by anthropogenic GHG emissions, some natural positive feedback loops would come into play, the most consequential of which would be the release of huge quantities of methane – a potent greenhouse gas – that for now remains sequestered in Arctic permafrost. Thresholds in the climate system, such as the melting of permafrost and glaciers, represent possible tipping points, that is, some attained levels of critical factors (in this case, global temperature) which when exceeded may result in abrupt and irreversible additional thermodynamic change, possibly even a "runaway" effect where the rate of change suddenly accelerates and cannot be brought under control. The thresholds most commonly referred to are either a 1.5°C (2.7°F) or 2°C (3.6°F) rise in average global temperature relative to the pre-industrial level. As with every other calculation in a risk scenario, this forecast comes with uncertainties and probabilities. Some people who live in cold climates may respond to these scenarios by saying either that such a warming would be welcome news or, alternatively, wonder why such a relatively small increase could be considered by scientists to constitute "dangerous interference" with the climate system. The scientists' answer is, quite simply, that one should pay attention to the trend line, below:

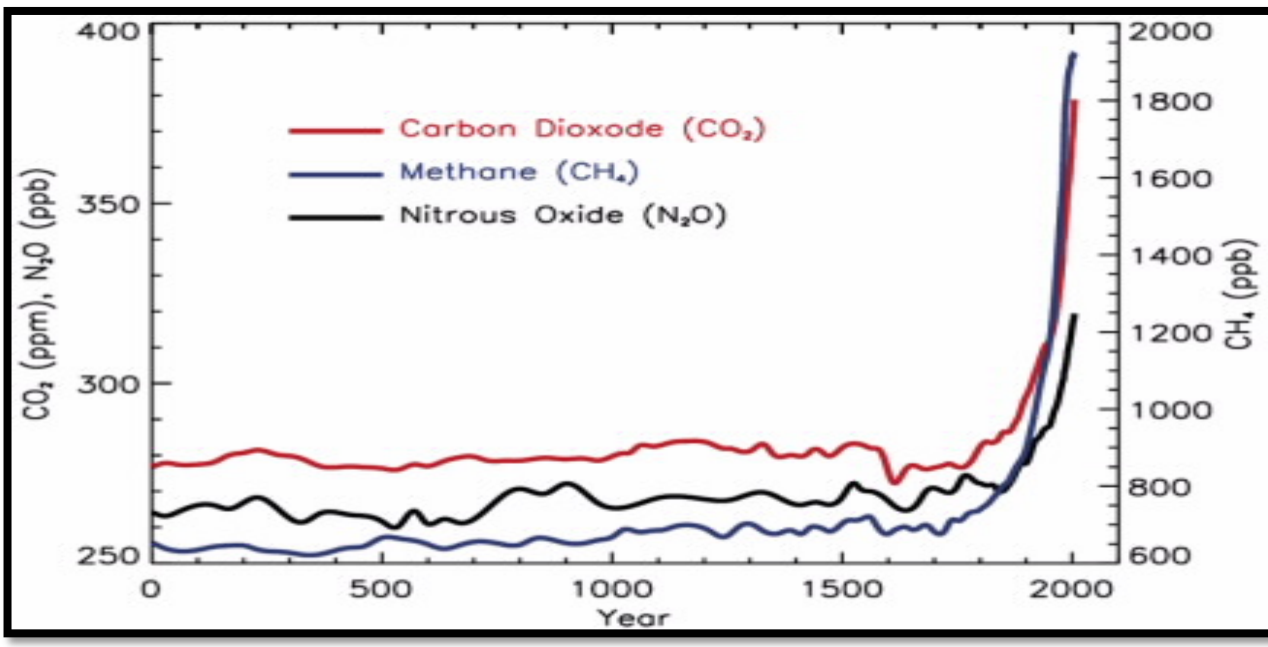

Figure 16: Atmospheric Concentrations of Greenhouse Gases

Lindsey 2018 comments: "In fact, the last time the atmospheric CO_2 amounts were this high was more than 3 million years ago, when temperature was 2°–3°C (3.6°–5.4°F) higher than during the pre-industrial era, and sea level was 15–25 meters (50–80 feet) higher than today."

The period in which the strong and persistent "uptick" begins to occur is the arrival of the Industrial Revolution around 1800. Because of thermal inertia, the concentrations will be rising for decades to come no matter what we do now; the rise will inevitably be translated into an increase in global average temperatures: A 1°C (1.8°F) increase over preindustrial levels has already occurred, and if current trends persist there is a risk that the climate system may become locked into a +1.5°C (2.7°F) threshold quite soon, sometime between 2020 and 2030. Does it matter that a 1.5°C rise would exceed the upper bound in the temperature variation that is estimated to have occurred during the entire Holocene, the period during which all of human civilization developed? But the temperature rise may not stop there: Unless actions are initiated soon, in order to begin reducing anthropogenic greenhouse-gas emissions so as to eventually stabilize the concentrations of these gases in the atmosphere (that is, preventing them from continuing to rise), a global average temperature increase of 2°C (3.6°F) above preindustrial levels may occur well before the end of the twenty-first century. Still, these can appear to be small increases, so do they matter, and if so, why?

Just how serious might a +2°C global temperature increase scenario be? Might a +2°C global warming be the level at which humanity unavoidably would be set on a course for a catastrophic future? A scientific paper published in 2018 (Steffen *et al.*) begins as follows:

> We explore the risk that self-reinforcing feedbacks could push the Earth System toward a planetary threshold that, if crossed, could prevent stabilization of the climate at intermediate temperature rises and cause continued warming on a "Hothouse Earth" pathway *even as human emissions are reduced* [WL italics].Crossing the threshold would lead to a much higher global average temperature than any interglacial in the past 1.2 million years and to sea levels significantly higher than at any time in the Holocene. We examine the evidence that such a threshold might exist and where it might be.

According to these scientists, passing the +2°C (+3.6° F) temperature threshold is likely to set in motion what they call "tipping cascades," which are certain positive biogeophysical feedback loops (permafrost thawing, loss of sea ice, release of frozen methane from oceans, etc.) that accentuate the trends in rising temperatures already occurring. Potential catastrophic effects following +2°C include sea-level rise as much as 6 meters, severe reductions in food output, and extensive dieback of both boreal and tropical forests. But the even more serious problem is that, once at +2°C the climate system may become locked into the "Hothouse Earth" pathway, causing more temperature increases that will be irreversible, the effects from which will persist for millennia thereafter.

The great risk is that humanity may turn out to be unable to mount effective counter-measures to avoid the dangerous "Hothouse Earth" pathway because the current *rates of change*, for both atmospheric CO_2 concentrations and temperature, are so high: Steffen *et al.* write that "these current rates of human-driven changes far exceed the rates of change driven by geophysical or biosphere forces that have altered the Earth System trajectory in the past," even exceeding the events which brought about the Paleocene Eocene Thermal Maximum, some 55 million years ago, when global temperatures were 8°C (14.4°F) higher than they now are. Faced with a high rate of change leading toward certain end-points, any efforts made to counteract the trend must be initiated sooner rather than later, scientists argue, or else one faces rapidly diminishing sets of opportunities to alter the trajectory of future events. As another group of scientists put it in a 2018 paper, we may be approaching the "point of no return" in climate change, the point at which we no longer have the option of avoiding future rising temperatures and catastrophic outcomes.

Many hundreds of scientists from around the world, drawn from a wide variety of academic disciplines, based in many different countries, have collaborated for decades on the extremely detailed overall assessments for climate science. Published papers on these subjects in peer-reviewed journals easily number in the thousands. The analytical methods they employ in this area are drawn from the shared, common stock of knowledge inherited from their predecessors over the past few centuries; the methods used by climate scientists are in every respect similar or identical to those used in every other contemporary scientific venture of discovery in physics and chemistry. The multi-disciplinary character of the climate science field is one of the attributes that protects it well from major interpretive error. For example, thermodynamics is one of the oldest core areas of modern science; it overlaps the fields of both physics and chemistry, and it is also an indispensable element in many modern technologies, including engines. Thermodynamic equations are used by climate scientists in their coupled general circulation models, and it would be easy for thermodynamics specialists who work in subfields other than climate studies to tell if the uses of those equations in these models were either inadequate or erroneous.

Yet many people – most of whom can claim little or no familiarity with the subject-matter of those sciences – call into question the results and predictions of climate science. Non-technical "sceptical" attitudes include the view that human actions cannot possibly be a decisive influence on the planet's climate as well as a questioning of scientists' motives. The awkward difficulty resulting therefrom is that, if the methods employed by climate scientists are erroneous or impure, then so are in equal measure the findings of all of their colleagues in related fields, including those that underpin all of the technologies and medical aids that these same doubters utilize and appreciate.

A scenario about the future which is probabilistic in nature, as all risk scenarios are, tells one that something harmful might occur later on unless steps are taken right away to head it off. It is not unreasonable, when faced with such a prediction, to ask whether one might wait for more certainty before acting. Whether or not this would be a prudent thing to do depends on the nature of the risk, however. Applying the "wait-and see" approach in the case of the climate system may be dangerous: For in delaying actions needed to reduce the risk one might arrive at a point in time when the harmful events cannot be avoided no matter what one does then.

This kind of bold and alarming prediction should give us pause. And then we might ask ourselves: Could the entire large group of scientists, living in many different countries around the world, who are responsible for predictions such as this one, be just plain wrong about climate change? This is by no means an unreasonable question to pose. After all, the history of modern science surely demonstrates that leading scientists of their day have been wrong at times about important points in their various disciplines. In physics, as late as towards the end of the 19th century, one recalls a widespread adherence to the theory of the "luminiferous aether," supposedly an invisible medium through which light was propagated; it doesn't exist. In chemistry, there was the phlogiston theory, used for about a century to explain combustion until being rejected in the late 18th century; until about the same time, naturalists believed that life-forms were fixed and did not evolve. Throughout the 18th century competing schools of thought in geology battled against each other for many decades. However, since the end of the 19th century the population of working scientists has increased enormously, having also expanded around the globe; the communications, frequent meetings, and joint publishing ventures among them have also been greatly strengthened. These and other factors make it much less likely that major interpretive errors will take root, persist and remain unchallenged in any scientific discipline.

And there is no doubt that science remains incomplete down to the present day: There are lively debates about the nature of physical reality in its smallest dimensions, the standard model of particle physics remains incomplete, relativity and quantum mechanics are not unified, and all physicists would love to know what dark energy and dark matter are. Much more remains to be understood in biochemistry (such as protein folding) and genetics (such as DNA repair) as well; there is reason to speculate that studies in the natural sciences, like other intellectual and artistic endeavours, will never be finished. And yet incompleteness, unsolved puzzles, and unresolved disagreements over specific points of interpretation are not the same thing as major interpretive error.

The climate-science community, like all scientific groupings, continually refine and improve the theories and methods they employ and develop new sources of relevant data. So, at any moment in time, one can expect there to be as yet undiscovered shortcomings in their collective work that will be overcome sometime later. *But is it possible or even likely that the current consensus among scientists seeking to explain climate change might turn out to be wrong in its entirety*? Less provocatively, we might appropriately ask: Even if one were to accept fully the contention that the earth has been warming somewhat since the late 18th century, and that this warming accelerated after 1950, could there be some simple, alternative explanations for these observed changes? For example, could they have resulted from purely natural processes, such as increases in solar radiation or something else? An answer is given in the major climate-science consensus documents, one of which is the U. S. *Climate Science Special Report*, issued in 2017 and available in its entirety on the Internet:

> Over the last century, there are no convincing alternative explanations supported by the extent of the observational evidence. Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and there is no convincing evidence

> for natural cycles in the observational record that could explain the observed changes in climate. (*Very high confidence*).

Of course, they could be wrong. Or worse: Have they been perpetrating an elaborate hoax on all the rest of us – and on the even larger group of their colleagues in all other fields of science? The modern scientific consensus on anthropogenic climate change has its origins in a famous 1957 paper by Roger Revelle and Hans Suess. If, sometime in the coming decades, this same scientific community investigating the climate comes upon new data and theories which call into question either or both the concept of climate forcing and the perceived need to drastically reduce anthropogenic greenhouse-gas emissions, we will know about these developments, because they will be published in the academic literature.

However, to contend that such contrary research findings, should they be made, could or would somehow then be suppressed, or that the current scientific consensus on climate change amounts to a gigantic hoax, is simply irresponsible and groundless. It is certainly the case that, occasionally, individual scientific papers which have undergone peer review, and have been published in a reputable journal, contain misrepresented or even invented data and are subsequently withdrawn, and that some of them amount to academic fraud. But it is impossible to imagine that this could occur on the scale of the thousands of papers on climate science that have been published since 1957. It is likewise impossible to imagine that all their authors have just invented the whole problem, so that at some point it will just go away of its own accord. To accept either of those propositions is to call into question the integrity of the entire process of modern scientific investigation since its sixteenth-century origins.

There are many comments in the preceding sections which call attention to one crucial aspect of the modern sciences, namely, that they must wrestle with the fact that the greater part of the reality of nature remains hidden – and deeply hidden – from our ordinary senses. The ways in which nature's many different operations actually produce the experiences of what we see and feel in the world around us are screened from view by an elaborate and somewhat misleading set of masks. The instruments devised to unmask these unseen realms began with simple telescopes and microscopes and advanced ultimately to the incredibly-complex particle colliders of today. Common sense asks: How can it be that the solidity of the material objects we handle every day is an illusion, because matter is mostly just empty space? How can it be that an invisible electromagnetic force, known to science as simply the strong force, holds together the constituent particles that make up atoms? How can it be that the world as it appears before out eyes is only a small part of what is happening in the universe, because the full electromagnetic spectrum contains many other dimensions – for example, x-rays and infrared radiation – that we cannot see unaided? All this and much more may be decidedly odd, when considered from the standpoint of common sense, but it is not possible to doubt that these are true statements.

The scientific study of climate is another mystery of this type. We cannot "see" climate; what we see and feel and hear is weather. Scientists "construct" past climate history from many inferences they draw out of the huge troves of evidence that are stored in the geological history of the earth – rocks, ocean sediments, tree-rings, long cores drilled from the ice sheets, fossilized plant and animal remains up to 600 million years old, and other data. They can tell us, for example, that without a doubt palm trees once grew in an ice-free Arctic region some fifty-three million years ago, when the climate there was like Florida is today, because they have found palm pollen in sediments on the ocean seabed just 500km from the North Pole. They can tell us what the atmosphere and the oceans were like hundreds of millions of years ago, because isotopes of oxygen and carbon are preserved in the shells of tiny creatures called foraminifera and diatoms. And so on and on. We cannot look around ourselves and see the climate history of the earth. That story is told in the planet's geological history as it has been reconstructed by generations of scientists. On the basis of that history, they have also made some educated guesses as to what the near future might hold for us.

Climate scientists have done their work and are continuing to do it. Sooner or later governments around the world, especially those in the nations which are the largest emitters of greenhouse gases (China and the United States), and their citizens (assuming they have a voice), will have to decide either to accept the scenarios and predictions summarized above or to ignore them – as they have the legitimate authority, and the legal right, to do. Climate scientists have provided a sense of the probabilities of the harms that await us as well as the level of confidence they have in those numbers. To be sure, despite the huge outputs of published research by many hundreds of these scientists, they may be wrong: It is possible that they have misinterpreted or exaggerated both the likelihood and the consequences inherent in the risks of climate change. The key questions for the rest of us are: How certain are we that they are just plain wrong? Or how certain are we that they have exaggerated the risk? Or worse, that they have constructed an elaborate hoax? If we are not certain, but just doubtful about what to believe, we might then ask ourselves: How long can we wait before making up our minds about this matter?

For some, climate-change skepticism means refusing to believe what is asserted in the consensus view of scientists. This view appears to be eroding, and as of now even a strong majority of U.S. citizens report to pollsters that they are convinced about the reality of global warming. But this amounts to only the first baby-step towards a conviction that policies and actions robust enough to bring about an end to rising GHG emissions will be supported. Unlike a belief in the credibility of climate science, a conviction that robust action of this kind is not only desirable but necessary means that citizens must pay the full economic and social costs required to make it happen. And many of us, even those in countries whose elected national governments support the appropriate public policy measures, appear to be still quite far from taking that next step.

Some say that we are running out of time during which to make any decisions to address climate change, but of course what they have to say on this point too may be wrong or misleading. And, to be sure, there is some possibility that, before any important deadlines have passed, the scientific consensus may change, then telling us that we need not go to the trouble of reining in our GHG emissions. Waiting for this possible change is nothing less than an ongoing wager on our future: We will have to bet on how likely it is that any dramatic change in the current scientific consensus on climate forcing will occur before all of us might have embarked irrevocably on a Hothouse Earth pathway. Our doing nothing now, or not enough to make a difference, or too late, can therefore also be framed as a wager on the future. Most of those alive today will have passed away before the worst of the predicted adversities may become apparent. Our children and grandchildren will be the ones required to reflect on how good the bet was.

TEN: A DAMAGED EARTH

The nature that is evident to our unaided senses here on our earthly home, in its vibrant colors, different ecosystems, and diverse populations of wild animals and plants, is *our* nature: It was made for us – coincidentally, randomly, accidentally, of course, entirely without the guiding forethought of a creator-god, but all the same it was made for us. The happy coincidence between the arrival of a geological cycle (the Holocene) welcoming to warm-blooded upright mammals, on the one hand, and the earlier evolution of a primate species equipped with a fecund brain, primed to exploit and even enhance the life-sustaining resources found at hand in its environment, on the other, was truly a fateful throw of nature's dice. The geological history of this specific planet, violently and repeatedly refashioning its crust and atmosphere across eons of time, and the complete evolutionary history of biological life on its surface, billions of years in the making, joined forces precisely at the right time to set the table for us, modern humans, allowing us to show how much we could do with the opportunity.

The timing was fortuitous indeed. The warm Holocene came about only 7,000 years after the Last Glacial Maximum, during which much of the Northern Hemisphere was cold and dry, with frequent dust storms; that was a frigid time during which humans already living in northern Europe were forced to retreat southwards, ending up huddling in caves in southern Spain and throughout the Mediterranean. As the earth gradually warmed during the long lead-up to the Holocene, and the Stone Age began, modern humans proved that they were ready to change in order to flourish and multiply: For at the onset of the Holocene, they were already transitioning from a wandering hunter-gatherer subsistence mode to a settled lifestyle supported by the domestication of plants and herding of animals. It took only another period of 7,000 years, starting about 10,000 BCE (when the human population is estimated to have been 2 million), to move from the earliest small settled groupings to the first complex civilizations of the early Bronze Age, in Mesopotamia and Egypt; by 3,000 BCE there were an estimated 45 million. The first civilizations had governments, laws, writing, monumental buildings, division of labor, and religion. How relatively quickly human societies developed during the early stages of the Holocene is truly astonishing. Their future development had already been prepared by the time the Holocene occurred, and when the warming took hold both their numbers and their intellectual and technological capacities exploded.

As for the rest of the universe, which admittedly had prepared all of the matter and energy resources out of which both we and our earth were molded, it was most definitely not made for us. But what does this matter? We are never going to travel to its distant environs, we are never going to live anywhere else except right here on our own planet. There is an inherent silliness in the contemplation of interplanetary and intergalactic travel. Go to Mars, for example, where gravity is one-sixth that on earth, where the landscape supports no biological life, and where the most characteristic climatic state consists in vast and prolonged dust storms; one could, of course, try living entirely underground there, until the effects of reduced gravity started to play havoc with one's body. Or go to Venus, where the surface temperature is 500°C; or to the gas giants, Saturn and Jupiter, where there is no solid surface. In intergalactic terms, the closest star to us is Alpha Centauri, and it happens to have an exoplanet in the habitable zone; but it is a mere 4.37 light-years (about 21 billion kilometers) distant, and one would have to be well-protected against bombardment by dangerous cosmic rays on the journey. Travel through wormholes in search of far-distant exoplanets which just might happen to sustain life-forms such as ours, and which not least also have the distinct advantage of being unoccupied, is just an innocent distraction from challenging and possibly devastating issues that almost certainly will need to be faced right here at home.

The notion that we humans may have damaged the planet on which we reside will seem odd at first hearing. After all, as reviewed briefly in earlier sections, we know full well that our earth has undergone many extensive geological transformations since its origins. Even if we accept the proposition that humans have now embarked on a pathway to the future that may undermine the established foundations of their present way of life, possibly drastically so, this means nothing with respect to the entirety of the earth itself: The planet's atmospheric and geological processes will adjust, as they always have done, and transition into some new equilibrium state. The larger-scale processes known to have occurred in the

Late Quaternary, that is, the repetitive glacial–interglacial 100,000-year cycles, either will persist long into the future, until there is a transition to a different state, or they will be disrupted relatively soon and transition more suddenly to the next state, whatever proves to be the case. In either case, the planet will carry on, except that there may be a new mass extinction of a large group of extant species; but that too has happened a number of times earlier, and the remnants of life too will carry on in new ways.

As noted, Steffen *et al.* (2015) have written: "The relatively stable, 11,700-yearlong Holocene epoch is the only state of the ES {Earth System] that we know for certain can support contemporary human societies." If what we are now doing is threatening the stability of the biogeophysical parameters that have sustained life on earth during the Holocene, the period during which humanity has flourished, multiplied, and created world civilizations, much of what now exists will not carry on. If this is indeed what we have set in motion, and if it leads us fairly soon to being immersed in Hothouse Earth, there will be a steep price to pay. In all likelihood modern humans will survive the coming test, perhaps in large numbers, although many other species we now share the planet with will go extinct. But many groups of people, as well as the international, national, societal, cultural and economic structures that now sustain them, will not. This is very likely to happen, beginning early in the twenty-second century, unless we resolve soon to take better care of the earth.

In saying this I am not advocating for some smarmy notion about "respecting" all life-forms or bowing down to worship our earth-mother. Rather, I mean simply that we should do whatever is necessary, and within our power to do, in order to maintain the Holocene earth comfortably within the global temperature range that has sustained human civilization to date. It is, quite simply and obviously, in our collective intelligent self-interest to accept this responsibility. If making an honest effort to do so entails experiencing disruptions in our established way of life, and incurring non-trivial economic and social costs, as it will, in order to accomplish this mission successfully and in a timely fashion, then this course of action ought to strike us as a task that ought not to be avoided and as a price that must be paid. To accomplish the mission, we not need invent or revive a religion but rather just put our trust in the general method of inquiry developed by modern science, as well as in the pure and applied scientific knowledge accumulated over the five previous centuries, that together have bestowed such blessings on so many aspects of our lives.

For us to care for the earth in a way that is consistent with the current scientific consensus on climate changes means to seek to restrain future growth in anthropogenic GHG emissions sufficiently so as to stabilize, as soon as possible, the level of concentrations of greenhouse gases in the atmosphere. We may fail to do so because nations allow GHG emissions to continue rising indefinitely and fail to agree upon a binding and enforceable international treaty is ever concluded for controlling emissions, with clear national targets and effective penalties for violating them. If we fail to satisfy these two requirements in the next twenty-five years or so, there is some probability that we will no longer be able to get off the Hothouse Earth pathway, no matter what we decide to do thereafter, either about rising GHG emissions or anything else. It is very likely that this is a path leading to severe flooding along all coastlines and the possible abandonment of major coastal cities everywhere in the world, as well as leading to sizeable reductions in worldwide food supply, widespread dieback of forests, major disruptions for marine life, and other consequences. It is very likely that such impacts will begin to be experienced before the year 2100.

And it is very likely that, if we have embarked on this pathway to Hothouse Earth during the second half of the twenty-first century, we will find ourselves unable to alter it. Another group of the climate-science consensus documents are the periodic, comprehensive five-year assessments issued by a large group of scientists assembled under the auspices of the Intergovernmental Panel on Climate Change (IPCC). In their *Fifth Assessment Report* (2014) we read: “Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.” But, of course, they could be wrong about this too.

Waiting to see whether or not we should worry about causing irreversible changes in the earth’s climate system is making a wager on the future. It is a bet, not a simple recognition of a perfectly obvious truth, because at the present time, or even sometime later, there cannot be complete certainty in the predictions made by climate scientists. To repeat, the scientists may possibly be wrong – either about human interference with the climate system, or about the predicted impacts by 2100 or thereabouts (including severe droughts and reductions in food supply, dieback of forests, serious flooding along coastlines), or both. Those who are not expert in the methods and results of climate science, as most of us are not, have to make a guess about whether the consensus view of this science is right or wrong. This guess amounts to nothing less than making a bet on whether there is a need to take specific steps so as to avoid a possible Hothouse Earth pathway. It is in essence a simple and straightforward wager. Choosing one side or the other does not require each of us, individually, to have the skills needed to fully understand the scientific theory of climate forcing or the quality of the evidence-base that has been assembled in order to validate it. Rather, all we need do is decide whether or not to put our trust in the enterprise of modern science.

Those of us alive today may think that a throw of the dice in the climate casino is a casual affair, a momentary act carried out before we turn our attention to more immediate concerns. None of our descendants, however, will be permitted to be indifferent bystanders when the results of this wager finally come in.

GUIDE TO FURTHER STUDY

Introductory Note.

In the age of good web browsers and an abundance of informative and reliable analysis, data, and commentary, readers have available to them all of the resources they require in order to form well-grounded views of their own on – literally – thousands of issues that may be of concern to them. To do so, readers need to develop their own skills in the task of discriminating among the sources they encounter in their web searches. As the author of this work, and as someone who has no training in the natural sciences, I routinely do so. In addition, even when a one carefully considers the credibility of sources encountered on the Web, she or he should be mindful of the fact that knowledge changes over time, as older sources are challenged, affirmed, or modified by more recent contributions; this applies to published materials from academic experts with good reputations as well as from other sources. Therefore, one should take note of the date of composition of the material, and, if the subject-matter is important to the reader, he or she should do additional searches so as to ascertain whether any specific contribution is up-to-date.

I became an academic researcher long before the World Wide Web appeared, but the techniques taught to young scholars – about critically assessing the credibility of the sources we consulted – remain valid in the age of instantaneous access. The techniques include asking whether a source indicates the nature and extent of the information base which is relied upon, comparing the resources on which different commentators rely, and critically evaluating the quality of a logical argument as it moves from analysis to conclusions. Above all, one should avoid relying solely on idiosyncratic accounts which report only the circumstances of individual cases. Another piece of advice is to make one's request, in the search line of the browser, as specific as possible.

In writing this essay I deliberately chose to employ as much scientifically-precise terminology as was suitable for the material being discussed. In doing so have relied on the fact that those reading an electronic file today can easily switch back and forth between the text in front of them and the WWW entries which explain technical terms. This is my own practice as a writer in the Internet age: For example, I search for terms such as "mitochondrial" or "taxon" before using them, in order to make sure that the definition and connotations are consistent with what I want to convey. While writing I also constantly recheck the data in reliable WWW entries for all of the substantive material on which I am relying, such as mass extinctions, Last Glacial Maximum, geological epochs, and so on. Readers of this essay are encouraged to do the same.

In this essay as in earlier writing I have found that, generally speaking, Wikipedia entries on scientific subjects are reliable and credible, not least because most of them are fortified with extensive references to published literature, and many of those references can be accessed by the general reader through hot links. Still, I almost always also consult other sources provided by the search results.

A. General Works.

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B. Sample of Academic Journal Articles and Web Resources.

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This was first an online magazine article in *New York Magazine*. Specific points in the first version were criticized by some climate scientists and others. I recommend that you read the annotated version of the magazine article, containing comments and discussion, at:

http://nymag.com/intelligencer/2017/07/climate-change-earth-too-hot-for-humans-annotated.html?gtm=bottom&gtm=bottom. The back-and-forth between author and critics, and the references for further reading that are cited, are useful and stimulating, even if one disagrees with the author's main thesis.

F. Public – Domain Sources for the List of Figures:

Figure 1: British Library: Matfre Ermengau, *Breviari d'amor* (France):
http://www.bl.uk/catalogues/illuminatedmanuscripts/ILLUMINBig.ASP?size=big&IllID=28755

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Figure 5: https://en.wikipedia.org/wiki/Lithosphere

Figure 6: https://en.wikipedia.org/wiki/Carbon_cycle

Figure 7: https://en.wikipedia.org/wiki/Greenhouse_effect

Figure 8: https://en.wikipedia.org/wiki/Phylogenetic_tree

Figure 9: Vostok Ice Core Data, East Antarctic Ice Sheet:
https://globalchange.umich.edu/globalchange1/current/labs/Lab10_Vostok/Vostok.htm

Figure 10:
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Figure 11: https://www.jpl.nasa.gov/news/news.php?feature=5210

Figure 12: https://www.carbonbrief.org/qa-how-do-climate-models-work/climatemodel

Figure 13: NASA = U.S., National Aeronautics and Space Administration:
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Figure 14: NOAA = U. S., National Oceanic and Atmospheric Administration:

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