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Introduction

1.1 The climate connection

Until the early nineteenth century, there was a widespread belief that the Biblical Flood was the greatest climatic catastrophe in human history. The deluge was supposedly God's punishment for the sins of man, and the story of Noah is the account of a family that in the face of mockery took drastic steps to ensure its survival and the preservation of life on Earth. This allegory was found to be an oversimplification when Baron Cuvier's studies of the Paris basin suggested that, for whatever reason, a *series* of deluges had altered the environment, so that it was, in turn, dry land, covered with fresh water, or inundated by the sea. However, beginning in 1836, studies of glaciers by Cuvier's student, Louis Agassiz, provided an alternative explanation for phenomena thought to be caused by flooding. Agassiz attributed glaciation to the divine hand, referring to it as 'God's Plough'. About 20 years later, Charles Darwin gave Agassiz's work an evolutionary interpretation, but Agassiz could not see the connection between climate and evolution.

Darwin's own work subsumed adaptation to climatic conditions as part of evolution, but he did not expand on the effects that the environment has on evolution. *The Origin of Species* (1872) is particularly weak on the evolution of physiological and behavioural adaptability; factors that are crucial for the survival of individuals during severe environmental changes. Furthermore, because he was a gradualist, Darwin paid little or no attention to catastrophic events in his theory. Although he assumed that human evolution was affected by climate, he did not explore the ways in which humans can change the climate.

In this book we examine both these connections: the impact of climate on evolution, with an emphasis on human evolution, and the impact of humans on climate. We are in the midst of a new era of climatic change, and modern society needs to assess its vulnerability and adaptability to such change. While technology has obviously advanced since the time of Noah, the task of adjusting to future

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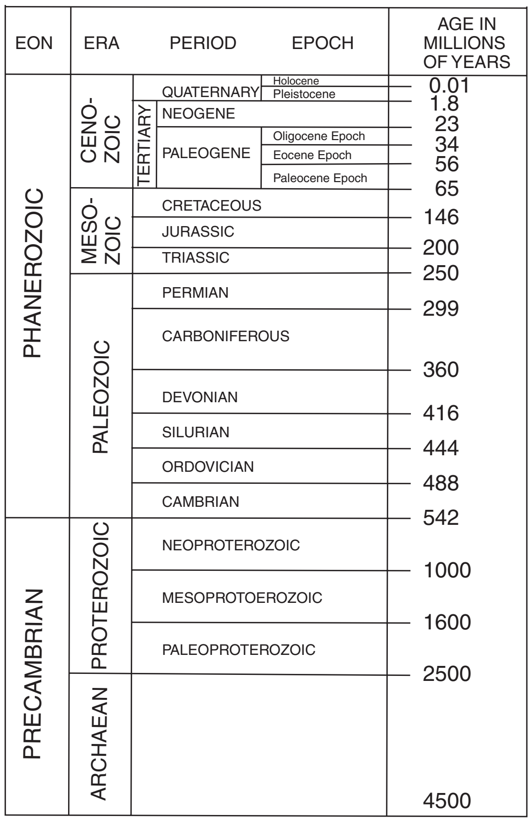

Figure 1.1 Geologic timescale

climate change will be no less challenging as we move down the path towards the eventual decarbonization of our global energy system.

1.2 Earth's changing climate

Climate change has been ubiquitous in Earth's 4.5-billion-year history (Figure 1.1). During the Archaean era there was little or no oxygen in the Earth's atmosphere, hence no ozone and no protection from solar radiation. However, after single-celled microbes invented photosynthesis, one of the photosynthetic by-products, free oxygen, gradually accumulated in the oceans and atmosphere.

In the late pre-Cambrian, most organisms were aquatic unicells, and the land-masses were cold, with a high albedo – bare rock, snow and ice reflected much of the Sun's heat back into space. A series of intense glaciations froze the surface water on the planet, creating what is known as 'snowball Earth'. The effect on life and its evolution at the surface of the oceans, except perhaps in a narrow equatorial zone, was devastating. Over the next several million years, the process of volcanic eruption and outgassing is thought to have slowly increased the atmospheric concentration of carbon dioxide until the greenhouse effect was sufficiently strong to melt the ice and bring the Earth out of its 'snowball' state. Atmospheric oxygen remained low as plants invaded the land, dispersed, evolved and increased in biomass. Gradually the amount of oxygen in the atmosphere increased until it eventually reached its present concentration of 21%, the rest being mainly nitrogen gas. Vegetation darkened the previously snow-covered landscape, decreasing albedo, and as a result the Earth became warmer.

The big bang of animal evolution occurred about 542 million years ago, at the beginning of the Cambrian period. Prior to that time, marine animals had been diversifying for maybe 100 million years. Land plants evolved during the Silurian about 444 million years ago. Plants, in the form of mats of fungi, bacteria and algae, inhabited the intertidal zone ever since the climate was propitious – within the range of supporting life. By 50 million years ago, Earth's climate was sufficiently warm that the Arctic experienced a Mediterranean-like climate with temperatures as high as 24 °C (Brinkhuis *et al*., 2006).

Five major extinction events are believed to be related to catastrophic climate events that were associated with bolide impacts or other geological events, including large volcanic eruptions that spewed forth huge lava flows (see, for example, Rampino *et al*., 1988; Rampino and Stothers, 1988). These occasioned some of the most sudden historical changes in Earth's climate, including mass extinctions of many species. The five major extinction events occurred at the ends of the Ordovician period (444 million years ago), Devonian period (360 million years ago), Permian period (250 million years ago), Triassic period (200 million years ago) and Cretaceous period (65 million years ago). The most extreme occurred at the end of the Permian and resulted in the extinction of 95% of the marine species known from the earlier Permian fossil record. While the impact of a bolide is only one of several mechanisms hypothesized as the cause of most extinctions, the impact of the Chicxulub comet in the Yucatan Peninsula is considered to be a potential cause of the Cretaceous event associated with extinction of the dinosaurs. In the North American splash zone of Chicxulub, higher-level plants are thought to have been exterminated, and the continent was populated by hardy ferns for millions of years. However, the work of Gerta Keller and associates found that the worldwide extinction of dinosaurs occurred some 150 000 to 350 000 years after the impact of the Chicxulub comet and suggest instead it may be due to volcanic outpourings in the Deccan trap terrain in India (see, for example, Keller *et al*., 2009).

Although these climate catastrophes wreaked havoc on the previously dominant species, their subsequent demise opened new environments for the lucky survivors. Those survivors that were adaptable enough to take advantage of the changed environment moved into the newly vacated territories. As a result, novel or previously

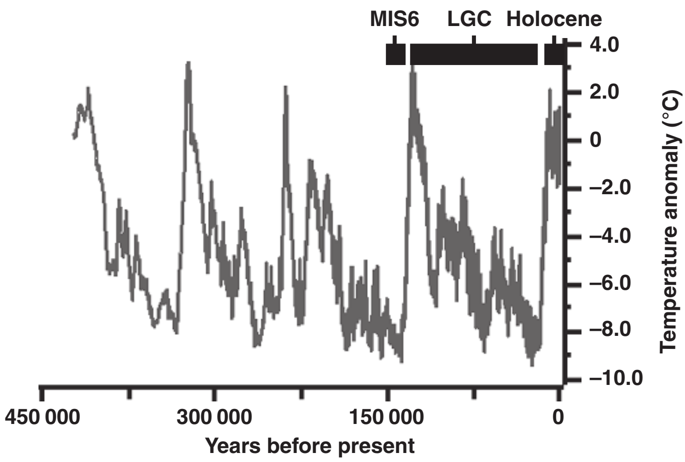

Figure 1.2 Temperature reconstruction of lower atmosphere over the last 450 000 years, expressed as an anomaly relative to present-day values. The data, described in Petit *et al*. (1999), is derived from analysis of historical stable isotopes from the Vostok ice core. Also indicated are marine isotope stage 6 (MIS6), last glacial cycle (LGC) and Holocene intervals.

rare species became widely distributed. After catastrophic changes, climatic stability allowed the surviving plants and animals to enter a prolonged period of evolutionary stability. This presented barriers to evolution, through competition by specialists, although a prolonged period of warm, stable climates was probably at the foundation of the emergence of homeothermy (warm-bloodedness) in birds and mammals (see 'Human adaptability', Appendix C, for a full account).

Continental drift, caused by the movement of crustal plates (i.e., plate tectonics), broke up the largest land masses, slowly affecting climate because the sea acts as a heat buffer for smaller bodies of land, and because of the redistribution of ocean currents. Furthermore the mountain building caused by movements of the crustal plates influenced global atmospheric winds, with a marked effect on precipitation, causing, for example, the monsoons of South East Asia and the drying of East Africa. By the time of the Pleistocene (1.8 million years ago), continental drift had produced a topography similar to what we see at present and had ceased to be a major factor in climate-induced evolution, except in areas where the plates crash together, causing earthquakes and volcanic eruptions.

Cycles of glacial and interglacial events have provided the largest changes in the climate of the Pleistocene. Interpretations of data from the Antarctic Vostok ice core by Petit and others (1999) and more recently from the Antarctic Dome Concordia ice core (Spahni *et al*., 2005) reveal large variations in the atmospheric temperature and carbon dioxide of the Antarctic during the past 650 000 years (Figure 1.2 and Figure 1.3). Six cycles of cold glacial and warm interglacial phases are evident during this interval.

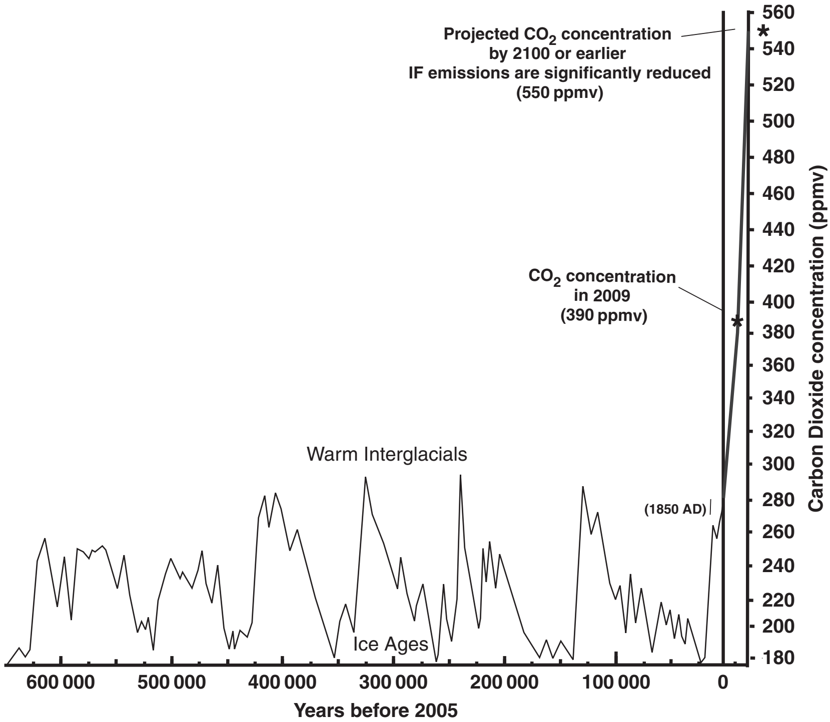

Figure 1.3 A composite atmospheric CO_2 record over 650 000 years – six and a half ice-age cycles – based on a combination of CO_2 data from three Antarctic ice cores: Dome C, Vostok, and Taylor Dome. Adapted from Siegenthaler *et al*. (2005, Figure 1.04). Also indicated are atmospheric CO_2 levels in 2009 and levels projected to be reached by 2100 or earlier.

1.3 Climate and humans

The global expansion and migration of *Homo sapiens* occurred during the last glacial cycle (LGC), which began 135 000 years ago (Figure 1.4). It was a time of significant global climatic change. The strength of the thermohaline circulation in the oceans, which directly influences the climate of the northern hemisphere, was highly variable. Global sea level rose and fell. Continental shelves were exposed for hundreds of kilometres in some areas and were submerged in others. Vegetation and animal distribution changed rapidly, sometimes decreasing biomass and sometimes increasing food resources for humans. Yet despite the variable climate and their prehistoric culture and technology, humans not only persisted but also spread throughout the world.

At the height of the last ice age, *Homo sapiens* had migrated out of Africa, colonized Asia and Australia, and begun moving towards the Americas. After the demise of the Neanderthals, *Homo sapiens* was the sole *Homo* species in Europe. More recently, a dwarf species of *Homo* lived on Flores Island. *Homo floresiensis*, a

PERIOD	EVENT	AGE IN THOUSANDS OF YEARS
QUATERNARY	*H. sapiens* reach New Zealand	0.8
	H. sapiens reach Hawaii & Easter Island	1.1
	H. sapiens reach Pacific Islands New Caledonia & Samoa	3
	Aboriginal peoples inhabit Canada's Arctic	6
	Short cold event	8.2
	Holocene warm interval & first agriculture begin, megafauna extinction in N.America	10
	H. floresiensis disappears	18–12
	Younger Dryas cold spell	12.7–11.7
	H. sapiens appear in the Americas	>20–10
	Coldest time of last ice age	21
	H. sapiens in NE Russia	32–18
	Neanderthals disappear	30
	H. sapiens in Tasmania	35
	H. sapiens appear in Europe, New Guinea	~40
	H. sapiens appear in Australia	~45
	H. erectus disappears in Java, cultural renaissance in Europe	after 50
	Behaviourally modern *H. sapiens* appear in China	~67–30
	Neanderthals in W. Russia until	~73–36
	H. floresiensis appears on Flores Island	74–38
	H. sapiens migrate out of Africa	~119
	Beginning of last glacial cycle	~135
	Modern humans appear in Africa	~195
	H. erectus disappears in China	230
	Neanderthals appear; *H. erectus* in Japan	by 500
	H. erectus on Flores Island	840
	Wooden javelins in Germany	900
	Homo erectus dispersal out of Africa	Prior to 1000
		1800
	Early stone tools	2300

Fig 1.4 Quaternary timeline

small-brained hominin, was only one-metre tall, walked on two legs, and was found associated with fossils of the Komodo dragon and a stone tool kit that was used to hunt the dwarf *Stegodon*, an elephant thought to have become extinct 840 000 years ago. *Homo floresiensis* survived on Flores Island from before 38 000 years ago until at least 18 000 years ago (P. Brown *et al.*, 2004), making them our last known living *Homo* relative.

1.4 Climate and species dominance

During the last 4 billion years there has been a series of dominant species on Earth. Although they were well suited to the stable environment in which they became ascendant, circumstances changed, and in the wake of major climate disruptions, the formerly dominant species' near or total extinction left an opening for adaptable survivors who could take advantage of the changed environment. For example, the climate catastophe at the end of the Cretaceous–Tertiary boundary 65 million years ago resulted in the extinction of large numbers of previously common species and an expanded distribution of new or previously rare species. Mammals and flowering plants were liberated from dynamic stasis that had restricted their distribution.

Homo sapiens has been the dominant mammalian species on Earth during only the last 10 000 years. In that time, humans have developed agriculture and domesticated animals; new civilizations and concentrated population centres have risen and fallen.

Generally, the biological response to a major climate disruption is a decrease in interspecific and intraspecific competition, usually because of the reduction in numbers, or the extinction, of previously dominant species. The result may be a per capita surplus of resources/biomass for the surviving species, although overall biomass may be severely reduced. New resource opportunities are created for use by previously non-dominant but adaptable species. Then, as climate begins to restabilize, populations of the most adaptable types expand.[1] The new dominant type diversifies as different populations specialize or adjust to the new conditions of life. These new changes begin to proliferate through speciation and behaviour modifications. As the climate restabilizes, circumstances become conducive to dynamic equilibrium or stability, which is strongly influenced by competition. This leads to the dominance of new species, expanded use of innovative behaviours, and an increase in populations of dominant species, which may, in turn, cause increased complexity of communities and ecosystems, and, therefore, larger biomasses and an increase in efficient use of resources.

For humans, the disruption of a stable climate puts a premium on physiological and behavioural adaptability, leading to the application of novel behaviours and new ideas that might have been obstructed as 'too revolutionary' or too much of a change from traditional practices in previously stable social groups. Some anatomical forms may become less common or disappear – e.g., gracile bodies in cold conditions; squat bodies in hot conditions. Migration from formerly supportive environments to a small number of refugia may result in the intermingling of previously isolated groups that have already developed novel tools and ideas. The combination of *crisis*, *communication* and *collaboration* is a powerful generator of emergent social novelty. New social wholes are greater than the sum of their parts.

As climate restabilizes, new human behaviours and techniques become traditional behaviours and techniques that are resistant to change. Populations expand, which may create economic stress (i.e., competition for resources) that brings internecine stress. This results in the emergence of new political organizations, such as social hierarchies involving division of labour and, consequently, a new distribution of resources. These developments put a premium on intergenerational transmission of knowledge (i.e., education).

During the last glacial maximum about 21 500 years ago, glacial ice covered much of the northern hemisphere. Subsequent climatic warming was interjected by a series of cold intervals caused by the injection of fresh water into the Atlantic Ocean, which interrupted its overturning circulation. The most renowned cold spike, the Younger Dryas, began about 12 700 years ago when the ice dam blocking massive Lake Agassiz in North America collapsed. It lasted just over a thousand years. Another cold event 8200 years ago resulted in a 4 °C drop in temperatures in Greenland for about 200 years. This short cold period interrupted the Holocene interval, an otherwise remarkably stable climate interval that has lasted nearly 12 000 years.

Coincident with the termination of the Younger Dryas and the onset of the relatively stable Holocene was the expansion of agriculture, which began between 12 000 and 8000 years ago at different locations around the world. This was the first time in Earth's history that a species consciously and systematically controlled its environment, generating additional stability in order to guarantee access to resources and increase the biomass of food plants and animals. The development of agriculture created a unique circumstance. Normally, climate stability would be conducive to dynamic stability and competition; biological communities would remain in a steady state for a prolonged period until the climate cycle disequilibrated things again. And in some sense this was true; the agriculturalists became dominant and killed off or otherwise outcompeted the hunter–gatherers. However, the onset of agriculture altered what was otherwise a stable state of resource availability, previously influenced only by climate.

In this case, climate stability facilitated the expansion of new ideas and technology (agriculture) that led to an increasing per capita surplus for *Homo sapiens*, a situation that previously occurred only when climate instability resulted in population declines. This surplus increased the region's carrying capacity for the native population, which in turn facilitated an increase in *Homo sapiens'* agriculturalist population and resulted in further control/manipulation of the environment and additional production increases. Population continued to grow, as did the number of population centres. This stimulated the development of innovative ideas in isolated population centres.

The cycle repeated. Self-induced states of disequilibrium, a consequence of the soil's increasing salt content and the depletion of natural fertilizers, led to conflict, disease and migrations away from environments that were no longer supportive. Migrating populations encroached upon fringe populations of non-agriculturalist aboriginal hunter–gatherers. The development of new civilizations in agriculturally rich regions again led to the acceptance of new behaviours and ideas, such as medicine and the use of fossil fuels. Populations increased again, further expanding the number of population centres. Groups placed increasing emphasis on accepted and successful industrialist practices. Migration was curtailed by political boundaries and the occupation of all available territories. Exploitation of fuels, minerals, timber and monoculture resources created a 'third world'. The population of this region had restricted access to technology and natural and medical resources, and its ability to migrate was limited to regions possessing less favourable conditions. Political instability was the common symptom of such limitations.

A noticeable effect of these later developments in human civilization has been climate change resulting from the use of fossil fuels and consequent greenhouse warming. Fossil fuels have been predominantly used by the industrialized nations as they developed their economies. However, the impact of climate change is global; it is not limited to 'first world' nations that may have the technological or economic ability to adjust to a changing climate. The seeds of discontent are therefore sown. These seeds could grow to resentment and hostility, or, if we take appropriate international steps to both mitigate climate change and assist non-industrialized nations in adjusting to its effects, they could blossom into a mechanism for creating global stability. In short, dealing with climate change is about dealing with domestic and global security.

1.5 What can be learned from evolutionary history?

Although this book is largely about climatic aspects of human history and the interaction between human activities and climate change, we must remember that we as a species are a recent step in the evolutionary journey and there were many pre-human interactions between environment and evolution. These early interactions provide us with principles that may help us understand the climate connection.

In the appendices on evolution, we discuss three arenas of evolutionary causation: developmental evolution; functional evolution, which incorporates physiological and behavioural causes; and association, which takes the form of symbiosis and socialization. All these evolutionary causes interact. They also operate within, and interact with, the physicochemical and biotic environment. In addition, all of them have molecular biological components.

We contrast two theories of evolution. The first, Darwinian theory, progenitor of the modern synthesis of evolution, emphasizes gradual change through natural selection over geological time. The second, emergence theory, treats evolutionary change as a saltatory (or rapid) process, combining internal organismal causes with environmental causes. Emergence theory therefore accepts the idea that the history of life takes the form of punctuated equilibria, with rapid emergent evolution punctuating the bulk of geological time, which is made up of states of dynamic stability in communities and ecosystems. The equilibrium phase is characterized by the operation of the syndrome of causes and effects generally referred to as 'natural selection'. However, natural selection is not evolutionarily creative, and emergent novelty is resisted by specialist organisms that are already highly adapted to prevailing conditions. Therefore for innovative evolutionary experiments to succeed, they must be able to either significantly outcompete the local specialists, hang on at the fringes where competition is reduced, penetrate new environments where resources are rich but competition low or benefit from natural catastrophes that either reduce the survivorship of dominant types or make them extinct. It follows that the greatest potential advantage of novel organisms is to be more adaptable than the older specialists. Emergent evolution can be shown to increase adaptability, often accompanied by multifunctional properties. But it does not follow that emergent types will enjoy immediate competitive success. This is illustrated by the coexistence of the mammals and dinosaurs through the Jurassic and the Cretaceous. Although more adaptable, the mammals could not become the dominant type until the dinosaurs had been wiped out at the end of the Cretaceous.

Emergence theory implies that with each major emergence there are not only novel qualities and interactions, but also a potential for further evolutionary diversification. However, emergences are largely unpredictable, and since they change the rules of the game, we can only gain a complete understanding of their evolutionary significance at the new emergent level. In our survey of evolutionary causes – developmental, functional and associative – we discuss the historical foundations of biological adaptability, which provides some general principles that apply to human evolution, despite the unpredictable nature of emergences. Adaptability is at a premium under conditions of stress and climatic instability, or on occasions where an unexploited new environment exists that cannot be entered by the specialists – only by organisms that are appropriately adaptable. The movement of physiologically adaptable animals from the sea to fresh water, or from fresh water to the land illustrates this point. Each migration removes competition and predation and makes new resources available. This mix of adaptability and migration applies to human evolution too. Even earlier in the history of life, the congregation of different types of microorganism potentiated symbioses that had greater adaptability and could exploit new environments. Indeed, all of the major ecosystems were founded on symbiosis. This too may be applied to human evolution: under stress conditions, formerly isolated groups might communicate and pool their resources, if they are wise enough not to kill each other off! Thus, crisis or catastrophe potentiates