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# Background to the Science of Environmental Change

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## 1 INTRODUCTION

This chapter has two main aims. First, it sets the scene for the Handbook by addressing three fundamental questions about environmental change. (1) What exactly is meant by the term 'environmental change'? (2) Why precisely is knowledge and understanding of environmental change so important to science and to society? And (3) what have been the main milestones and paradigms in the development of the field? The second aim is to outline the organisation of the Handbook, which attempts to provide, in two volumes, comprehensive coverage of the present state of scientific knowledge and understanding of environmental change while emphasising current priorities and trajectories of research.

## 2 DEFINING ENVIRONMENTAL CHANGE

The term environmental change means different things to different people. In this Handbook, use of the term is not limited simply to the relatively recent changes in aspects of the environment that affect, or are affected by, the human population. Instead, the primary concern is with the science of environmental change *sensu lato* based on the following broad definition: the study of changes in the geo-ecosphere, together with their actual and potential interactions with people.

The concept of an Earth 'sphere' was first introduced by Suess (1875) in the context of the geological evolution of the European Alps. The geo-ecosphere, or global geo-ecosystem, is a relatively new concept that encompasses the several individual spheres – atmosphere, hydrosphere, cryosphere, lithosphere, biosphere, pedosphere, and so on – that are commonly identified as interacting components of the biophysical (or natural) environment at the Earth's surface (Figure 1.1a). The term geo-ecosphere is preferred to ecosphere, because it gives greater weight to the physical systems in their own right, rather than merely the non-living components that interact with the biosphere (cf. Huggett, 1999).

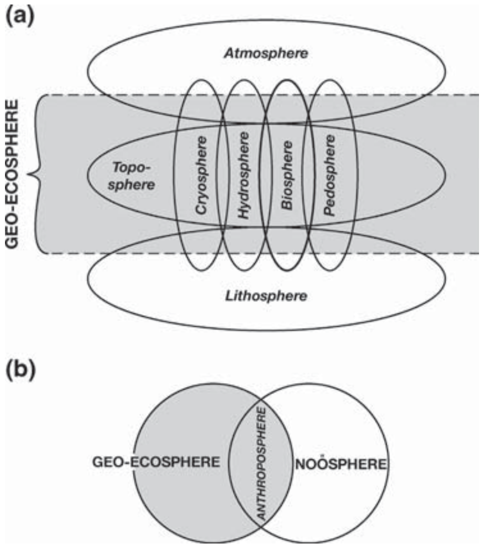


**Figure 1.1 Earth spheres, the arena of environmental change: (a) the geo-ecosphere and its component 'spheres'; (b) the human-influenced geoecosphere, or anthroposphere.**

*Source*: Matthews and Herbert (2008).

There may not be universal agreement on use of the term geo-ecosphere for our object of study but it reflects well the recent recognition of the need for integration of the various disciplines involved in the study of the changing environments of the Earth. This need has been widely recognised in the Earth sciences, for example, by the formation of the relatively new Biogeosciences Section of the American Geophysical Union (AGU) and the similar Biogeosciences Division of the European Geosciences Union (EGU). The Biogeosciences Section of the AGU emphasises the biological aspects of the Earth sciences, especially biogeochemistry, biogeophysics and planetary ecosystems. Indeed, its goal is to address better the interactions of humans with climate, hydrology and ecosystems, and to provide a scientific forum for environmental policy (http://www.agu.org/sections/biogeo/index.html).

Interactions with people are introduced in Figure 1.1b, which defines the anthroposphere as the 'human-influenced geo-ecosphere'. Several terms have been used for the human sphere itself: here we use the term noösphere for the sphere of influence of the human mind (Samson and Pitt, 1999; Teilhard de Chardin, 1956; Vernadsky, 1945). The noösphere therefore includes human thoughts, opinions, actions and policies relating to environmental change, whereas the anthroposphere may be considered as carrying the biophysical imprint of these human dimensions of environmental change. Changes in any or all of the 'spheres' within both the natural geo-ecosphere and anthroposphere are parts of environmental change according to our definition. Because of the extent and complexity of the interactions between the various spheres, much environmental change research is now viewed as part of Earth system science. This focuses on the geo-ecosphere and anthroposphere as a whole rather than on the component parts (see later section on the development of Earth system science). Of particular importance is interdisciplinary research on process interactions and the dynamics of the geo-ecosphere, co-evolution of the physical landscape and the biosphere, and likely future change (cf. National Research Council, 2010). The human dimensions of environmental change are increasingly important, as is made clear below, but there are other dimensions that need to be considered.

Timescales and spatial scale need to be taken into account in any consideration of environmental change. The study of environmental change includes investigating changes of the geological, archaeological and historical past, and those that may happen in the future, on various timescales. Some changes, such as those associated with continental drift and evolution, may take millions of years and, for much of the time, have proceeded without being influenced by people. Other changes in the geological record, such as those associated with the onset or termination of stadials and interstadials, may have occurred within a decade or less, and some of these abrupt changes also occurred long before the human species evolved (National Research Council, 2002).

In relation to spatial scale, environmental changes range from local, through regional, to global and, in the future, will affect different places on Earth in different ways: from polar ice sheets to tropical rain forests, and from the highest zones of terrestrial mountains to the deepest marine environments. The term 'global environmental change' has been used in a variety of ways (Goudie, 2009). Here a geocentric definition is offered, based on Turner et al. (1990a), as 'any natural or anthropogenic environmental change that affects a global-scale biophysical system (a systemic global change) or the effects of which become global in extent (a cumulative global change)'. Systemic global changes include the climatic effects of major volcanic eruptions, enhanced emissions of greenhouse gases to the atmosphere from industrial sources, and changes to the oceanic circulation; cumulative global changes include deforestation and its effects, such as soil erosion and biodiversity loss.

Environmental change is, in many ways, a complex series of interacting processes and a bigger topic than merely those aspects impinging on humanity. The *Handbook of Environmental Change* reflects the broad and long view of the science of environmental change, while taking full account of the human dimensions. Some emphasis is given, however, to change in the recent past and the immediate future, where natural biophysical change interacts with human populations.

## 3 SCIENTIFIC IMPORTANCE AND SOCIETAL RELEVANCE

There are two basic reasons why knowledge and understanding of environmental change are so important: first, environmental change presents major scientific questions that stretch our curiosity to the limit; and second, it poses major practical problems for people and society and, particularly in relation to climate change, is arguably the most important issue facing humanity today.

Because most aspects of the environment evolve constantly, knowledge of environmental change is fundamental to understanding how the geo-ecosphere works. The most important scientific questions generally focus on the pattern, timing, causes and mechanisms of environmental change. These questions present huge challenges to science and to the human intellect.

Not least of these scientific challenges are the complexities of the interactions within the geo-ecosphere as an Earth system in which human populations, activities and effects are component parts. Most successes from the application of scientific method in the past have been based on the analysis of relatively simple systems using a reductionist approach (Pickett et al., 2007). Scientific methods appropriate to understanding ecosystems, geo-ecosystems and other holistic entities with their potential for complex interactions (Mitchell, 2009) and so-called emergent properties (Bedau and Humphreys, 2008), are at a comparatively early stage of development. So are the methods appropriate to those scientific fields with important temporal dimensions involving, for example, reconstructing and explaining past events (Inkpen and Wilson, 2009). Scientists asking questions about palaeoenvironmental or future events rarely have the opportunity to conduct classical experiments; but they can utilise natural experiments (Deevey, 1969; Diamond and Robinson, 2010) and computer modelling (Bartlein and Hostetler, 2004; Hargreaves and Annan, 2009; Knutti, 2008; Street-Perrott, 1991) to develop and test their hypotheses and conclusions. Furthermore, the human dimensions of environmental change research, such as explaining past human–environmental interaction, require cooperation between science, social science and the humanities, to develop hybrid methods of analysis and synthesis (see, e.g., Endfield, 2008; Head, 2000).

Many practical problems for society today stem from the fact that anthropogenic causes have become increasingly dominant over the natural causes of environmental change during the last *c.*11,500 years of the Holocene (Alverson et al., 2003; Messerli et al., 2000; Roberts, 1998; Simmons, 2008), during the last two or three hundred years of the Anthropocene (Crutzen and Stoermer, 2001), and especially during the last 60 years or so since the mid-twentieth century (McNeill, 2000; Oldfield, 2005; Steffen et al., 2004). From the mid-Holocene onwards, at first agricultural and later industrial societies, altered the nature of the interaction between people and the biophysical environment as their relative impact reversed (Figure 1.2). Hunter–gatherers lived within largely natural geo-ecosystems with a high level of dependency on their biophysical surroundings. Urban–industrial societies live farther apart from nature in built environments, and their relationship with the biophysical environment is dominated by major human impacts. Cultural landscapes, especially traditional agro-ecosystems, are intermediate in character. Cultural anthropologists identify similar patterns of interaction in the context of contemporary human societies with different economic systems and lifestyles (Crate and Nuttall, 2009; Peoples and Bailey, 2006).

The scale of human impact on the environment differs between the various Earth spheres, rates of change have varied through time, and there have been major differences in the nature and rate of impact at the regional scale (see, e.g., the major assessments of Goudie, 2007; Thomas, 1956; and Turner et al., 1990b). Nevertheless, through time, the systemic and cumulative effects have become greater and increasingly global, as human impacts altered not only the structure but also the processes of the geo-ecosphere, its energy flows and its biogeochemical cycles (Oldfield, 2008). These interventions sometimes had irreversible and disastrous consequences for people, but sometimes societies showed remarkable resilience in the face of both natural and anthropogenic environmental changes (Diamond, 2005; McAnany and Yoffee, 2010; Rolett and Diamond, 2004; Schwartz and Nichols, 2006; Tainter, 2006). The present

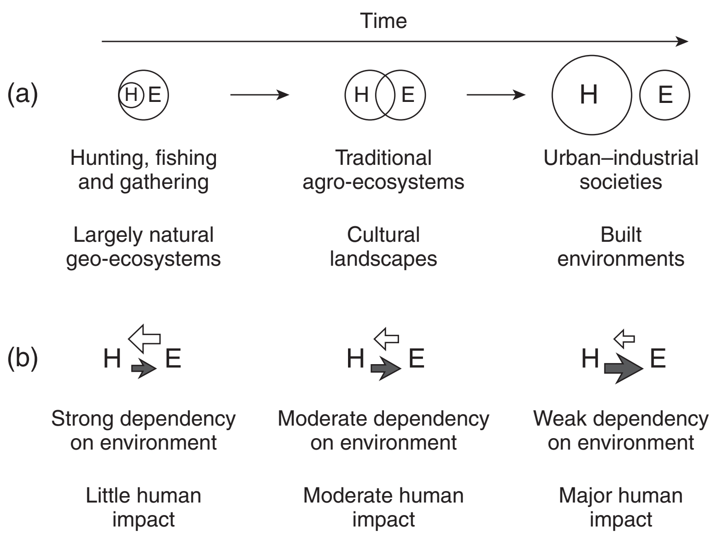


**Figure 1.2 People-environment interaction during the Holocene: (a) the changing nature of the interactions between human populations (H) and the biophysical environment (E); and (b) the relative scale of the respective impacts.**

*Source*: Roberts (1998).

and future state of the biophysical environment is increasingly dependent on this human impact and on the policies, in place or otherwise, to counter adverse impacts.

Climate change in general and global warming in particular hold a special place in the catalogue of human impacts on the environment because the consequences for humanity could be more disastrous than was the case with any other previous impact. Until recently, the nature and scale of the human impact was in doubt (see, e.g., Idso, 1988). However, the scientific community is now almost unanimous in its belief in global warming and in the attribution of the cause to the anthropogenic enhancement of greenhouse gases in the atmosphere; it is also gaining confidence in the predicted impacts (World Meteorological Organisation, 2003; Arctic Climate Impact Assessment, 2004; IPCC, 2007a, 2007b). During the twentieth century this impact truly became 'something new under the Sun' (McNeill, 2000), but what to do about it, and how to adapt and mitigate the effects, is much less clear (IPCC, 2007c; Giddens, 2009; Lomborg, 2001, 2007; Stern, 2007). The cultural, social, political and ethical reasons for why people disagree about climate change and what to do about it (Hulme, 2009) are largely beyond the remit of this book but are clearly relevant to the actions that have been taken so far and will be taken in the future in relation to mitigation policies.

At the present time, despite the existence of the scientific and technological know-how to counteract most of the world's problems associated with environmental change – such as deforestation, desertification, soil degradation, habitat and biodiversity loss, water pollution and global warming – countries in all states of development remain vulnerable to environmental change. In addition to these types of environmental change, extreme events with a purely geophysical origin cannot be neglected. The effects of the Boxing Day tsunami around the coast of the Indian Ocean in 2004, Hurricane Katrina in the southern US in 2005, the Haiti and Chilean earthquakes of 2010, and the Japanese earthquake and tsunami of 2011, demonstrate the vulnerability of human populations to extremes in various components of the Earth system, some of which may be linked to anthropogenic origins. Environmental variability from gradual climatic changes to natural hazards and extreme events has affected human societies in the past and will continue to do so in the future (e.g., Caseldine and Turney, 2009; de Menocal, 2001; Diaz and Murnane, 2008; Dillehay, 2002; Grattan, 2006; Torrence and Grattan, 2002). It is necessary, therefore, to understand fully all the dimensions of environmental change. This Handbook focuses on the scientific basis of that understanding: a companion volume (Pretty et al., 2007) focuses on the cultural, social, political and ethical factors that influence how that information is used. Clearly, the first requirement of any decision making is a clear understanding of the science behind the phenomenon of environmental change, and that is the first priority of this Handbook.

## 4 HISTORICAL MILESTONES AND PARADIGMS

Tracing the development of the multidisciplinary and interdisciplinary field of environmental change is a particularly difficult task in light of the wide range of disciplines and specialisations involved. Although there was earlier awareness of change in the environment, particularly from the field of geology, the beginning of modern scientific ideas about environmental change can arguably be placed in Switzerland in the early nineteenth century with the advent of the glacial theory, which was developed by various members of the Helvetic Society (see, e.g., North, 1943).

Taking a lead from the uniformitarianism of James Hutton and Charles Lyell, glacial theory was formulated with important contributions by, amongst others, Jean-Pierre Perraudin, Ignace Venetz, Jean de Charpentier and Louis Agassiz. They rejected the previous pseudo-scientific, catastrophic and semi-religious diluvial theory, which had explained the disposition of landforms, sediments and fossils in terms of their temporal relationship – antediluvial, diluvial or post-diluvial (later alluvial) – to the biblical flood of Noah. On the basis of polished, striated and grooved rock surfaces, as well as the unsorted nature of glacial sediments, erratic boulders and related evidence of glacial erosion and deposition, they argued that Alpine glaciers formerly extended far beyond their contemporary limits. This evidence was linked to glacier expansion and to the existence of a relatively cold climate or Ice Age, during which iconic mammals (such as mammoths) thrived. This, in turn, soon led to the idea of interglacials and early notions of climatic change as the primary driver of many other environmental changes throughout the geo-ecosphere, often far removed from the centres of glaciation (see especially, the detailed account in Imbrie and Imbrie, 1979; and the earlier summary in Flint, 1957). These associated changes included, for example, major shifts in location of the Earth's biomes in response to changing climates; global glacioeustatic sea-level change in response to changing ice volume (with consequent opening and closing of land bridges, such as the Bering Strait and the English Channel); regional and local glacioisostatic adjustment of the land surface height and relative sea level in response to variation in the weight of ice masses; and hydrological change at lower latitude leading to changing river regimes and lake levels. All of the listed environmental changes were recognised within 30 years of the publication of *Études sur les Glaciers* by Agassiz in 1840 (Carozzi, 1967).

The shift from the diluvial theory to the glacial theory is therefore considered to constitute the first paradigm shift in the study of what is currently understood by scientists as environmental change. Both theories had all the features of a paradigm (*sensu* Kuhn, 1962) in that they provided different, relatively stable frameworks for research, separated by a scientific revolution in the questions posed and the approaches used in problem solving. The glacial theory presaged a raft of further new developments that led directly or indirectly to the diversity of concepts, theories and methodologies that today characterise the science of environmental change (Figure 1.3).

The history of the science of environmental change therefore not only reaches far back into the geological past but also extends forward to the present preoccupation with global warming and other current environmental concerns involving the future of humanity. Not all the 48 developments (49 including the glacial theory itself) identified in Figure 1.3 can be said to have brought the necessary revolutionary change across the whole field to be characterised as new paradigms. Hence, no distinction is made between paradigms and those developments that fall short of full paradigm status, which are termed 'milestones' or major developments of lasting influence (cf. Birks, 2008, who recognised 14 paradigms in the development of Holocene palaeoclimatic research alone).

Three developmental strands are suggested in Figure 1.3 from shortly after the glacial theory emerged less than two centuries ago to the three major interacting and mutually reinforcing subfields of the early twenty-first century, namely Quaternary science, Earth system science and sustainability science. Much of the emphasis in Quaternary science is on the understanding of past changes based largely on environmental reconstruction and dating. Earth system science focuses especially on understanding the processes and mechanisms of global change, often using sophisticated environmental modelling and monitoring. Sustainability science is concerned with understanding the interactions between people and environment (the human dimensions of environmental change) with a view to a sustainable future. Our recognition of three developmental strands should not be seen, however, as an attempt to preserve the historical discontinuities that existed between these strands in the past.

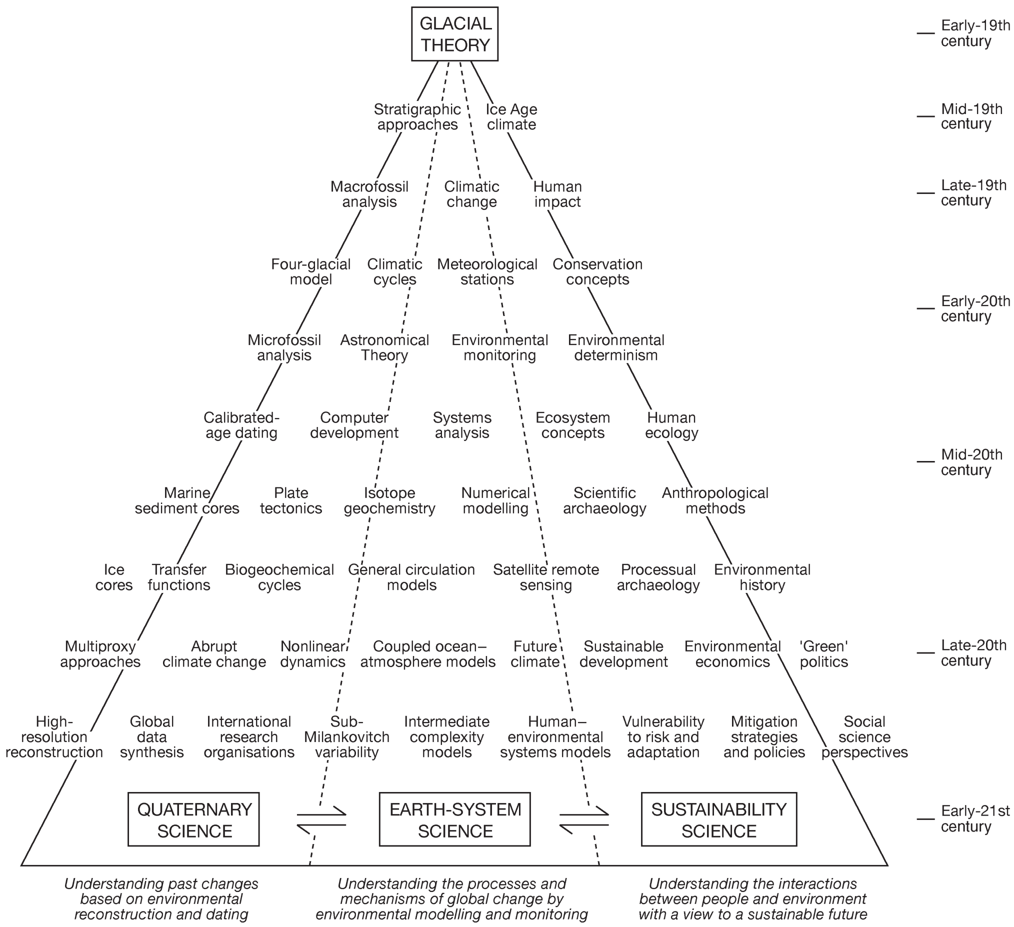


**Figure 1.3 Schematic representation of the development of environmental change as a field of study over the last two centuries: 49 specific developments (milestones and paradigms) are shown; the three segments of the triangle suggest three developmental strands from the Glacial Theory towards the three current interacting subfields of Quaternary science, Earth system science and sustainability science; an approximate timescale is shown at the right margin.**

## *4.1 The development of Quaternary science: understanding past environmental change*

Quaternary science is undoubtedly the most firmly established of the three subfields. It is characterised by a well-developed knowledge base, a wide variety of methods for environmental reconstruction and dating, and many well-tested theories (see, e.g., the overviews provided by Anderson et al., 2007; Bradley, 1999; Elias, 2007; Lowe and Walker, 1997; and Williams et al., 1998).

Two Scandinavian botanists, Axel Blytt and Rutger Sernander, are arguably the fathers of modern approaches to environmental reconstruction in general and palaeoclimatic reconstruction in particular. Towards the end of the nineteenth century, they used the stratigraphic analysis of macrofossils in peat bogs to divide the Holocene into intervals of varying warmth and wetness

(Birks, 2008). Their work was followed by the introduction of pollen analysis which, by the mid-twentieth century, was very widely used throughout the world for reconstructing vegetation history and inferring the relative and interacting roles of both climatic fluctuations and human impacts. A wider range of microfossils – from the full range of natural archives from terrestrial, lacustrine and marine environments – were brought into use later.

Building on the earlier ideas of James Croll, the early twentieth century also saw Milutin Milankovitch, a Serbian mathematician, complete the astronomical theory, which offered a comprehensive explanation for the periodic alternation of glacial and interglacial climates (Imbrie and Imbrie, 1969; Petrović and Marković, 2010). However, the theory, based on the effect of orbital parameters (precession, obliquity and eccentricity) on solar insolation received by the Earth from the Sun, was resisted by the scientific community for many decades before it became the established paradigm that it is today. Major reasons for delayed acceptance included: (1) the existence of plausible rival hypotheses; (2) the scale of the forcing was believed inadequate, despite the notion of amplification by the carbon cycle having already been introduced by T.C. Chamberlin (1897, 1899); and (3) the lack of suitable data from the geological record with which to test the theory empirically.

Working on varve sequences from lake sediments at the beginning of the twentieth century, Gerard de Geer, a Swedish geologist, made the first realistic estimate of late-Quaternary time (Walker, 2005). He defined the term varve as consisting of an annual sediment increment with distinct summer and winter layers, coined the term 'geochronology', was the first to use an annually resolved timescale in geology and used this to estimate the time elapsed since the termination of the Pleistocene (Zolitschka, 2007). However, it was the invention of radiocarbon dating and other radiometric dating techniques from the mid-twentieth century onwards that enabled the widespread development of precise chronologies based on absolute or calibrated-age dating. A full range of dating techniques is now available to Quaternary scientists of all persuasions (see, e.g., Beck, 1994; Noller et al., 2000; Taylor and Aitken, 1997; Wagner, 1998; Walker, 2005).

Evidence from the marine environment could not be fully exploited until after 1968, when the Deep Sea Drilling Project (DSDP) commenced and long marine sediment cores were retrieved from the ocean floor for the first time (cf. Emiliani, 1955). In contrast to terrestrial records of environmental change, the advantage of marine records lay, above all, in their continuity, potentially through the whole of the Quaternary and beyond. They were also intimately associated with development of the geophysical theory of plate tectonics, which is important for understanding many aspects of long-term environmental change, including mountain building, seismic and volcanic activity, and landscape evolution (Van Andel, 1994). Marine records enabled, in particular, the recognition of over 40 glacial and interglacial episodes; whereas a maximum of four (Gunz, Mindel, Riss and Würm, to use the Alpine terminology) had been recognised from terrestrial records for most of the previous half century. They also enabled a convincing test of the astronomical theory, using the isotopic composition of microfossils (foraminifera) as evidence of ice volume on land and the palaeomagnetic record to establish firmly the timescale (Hays et al., 1976). Marine sediment cores and long sedimentary sequences from the Ocean Drilling Programme (ODP; 1985–2003) and the Integrated Ocean Drilling Program (IODP; 2003–2013) continue to provide important evidence for the long-term pattern and timing of environmental change from the marine realm, including the roles of marine processes, ocean circulation patterns and ocean–atmosphere interaction in global climatic change (see Ocean Drilling Programme, 2007).

Results from the analysis of ice cores from the Greenland and Antarctica ice sheets, which were published from the late 1960s onwards (e.g., Dansgaard et al., 1969), produced continuous environmental records for the last several glacial–interglacial cycles, generally with much higher temporal resolution than the marine records. Past atmospheric composition, including levels of greenhouse gases, sulphates and dust from volcanic eruptions, and heavy metal pollutants, are amongst the information that is well represented in ice-core records. Abrupt climatic oscillations at sub-Milankovitch frequencies (in the form of Dansgaard–Oeschger events), which indicate potential instability in the Earth–ocean–atmospheric system, were first convincingly demonstrated from ice-core data (Dansgaard et al., 1969, 1993). Sub-Milankovitch palaeoclimatic events of regional if not global extent are increasingly recognised, not only from previous glacials and interglacials but also from the Late Glacial and Holocene, including Heinrich Events, Bond cycles, neoglacial events and the ‘Little Ice Age’ (Alley, 1998; Andrews, 1998; Bond et al., 1993, 2001; Heinrich, 1988; Matthews and Briffa, 2005; Matthews and Dresser, 2008; Roberts, 1993).

Ice-cores also yield reconstructions with annual resolution and therefore examples of the ultimate high-resolution reconstruction (see, e.g., Alley, 2000; Mayewski and White, 2002; Loulergue et al., 2008; Lüthi et al., 2008; Steffensen et al., 2008). This type of reconstruction has recently become a high priority for understanding climatic variability over the last millennium in the context of the detection and attribution of possible abrupt future changes in the environment, especially climate (Jones et al., 2009). Most natural archives yield information that falls short of this ideal. The study of tree rings (dendrochronology and dendroclimatology), which has a relatively long history, is probably the best-known source of high-resolution reconstructions. Microdendroclimatology (Loader et al., 1995) is even capable of reconstructing seasonal climatic differences. Varves, other annually laminated sediments, corals and speleothems are the other main sources of records with annual time resolution (see, e.g., various chapters in Mackay et al., 2003).

Reconstruction of environmental change from peat, ice, marine and lacustrine sediments, loess and the other natural archives, today typically adopt a multiproxy approach, whereby many different types of information are derived from the same archive (Guiot et al., 2009). This permits the mutual validation of proxies, as well as providing a firmer basis for understanding the past events themselves and their forcing factors. Often an integral part of a multiproxy approach has been the development of new and sophisticated physical, chemical and biological techniques to prepare samples and extract the required environmental information. This is typified by the widespread use of isotope geochemistry in association with ice and marine cores, and in palaeolimnology (Leng, 2005) and dendrochronology (McCarroll and Loader, 2004), which has greatly extended the reach of the traditional approaches associated with these archives. Similarly, the development of multivariate transfer functions in relation to marine and lacustrine sediments, pollen and tree rings has greatly improved the ability to make precise numerical estimates of past environmental variables from modern data (see, e.g., Birks, 2003). This development may be considered to be a recent manifestation of long-established uniformitarian principles.

The final recent developments in Quaternary science to be highlighted in Figure 1.3 involve the way research is organised, rather than the research itself. Two particularly important aspects of this that have changed are: first, the use of databases to achieve data synthesis up to global scale and, second, the growth of formal, international organisations to coordinate research internationally (Perry, 2002). Both developments may be regarded as a response to the growing interest in global patterns and processes, together with the need to share the cost of expensive activities and avoid continually reinventing the wheel. This internationalisation of research is an equal, if not even more prominent, aspect of Earth system science and sustainability science.

## *4.2 The development of Earth system science: understanding the processes and mechanisms of environmental change*

Earth system science emerged as a subfield in the study of environmental change late in the twentieth century. The essential characteristic of Earth system science is the integrated investigation of the geo-ecosphere as a single, interacting system (Earth System Sciences Committee, 1986; Jacobson et al., 2000; National Research Council, 2010; Schellnhuber and Wenzel, 1998; Schneider, 2000; Steffen et al., 2004). It focuses on the dynamic components of the geo-ecosphere – the processes and mechanisms of change in the global context – with some emphasis on biogeochemical cycles within the system, on the Sun as the primary energy source, on people as an integral component and on the Anthropocene timescale. The iconic diagram of the Earth system proposed by Bretherton (1985; Earth System Sciences Committee, 1986; Schellnhuber, 1999; Wainwright, 2009) provides a schematic representation of the complex interactions involved (Figure 1.4).

Prior to the late-twentieth century, both the conceptual and technical bases for such an integrated view were poorly developed. The ideas that the various components of the geo-ecosphere interact and that climatic change was an important driver of environmental change nevertheless became firmly established as soon as the global implications of the glacial theory emerged in the late-nineteenth century (Figure 1.3). Regular cycles or periodicities in climate and weather associated, for example, with sunspot or lunar cycles were also recognised early on (Burroughs, 1992). Although the existence of some proposed cycles has been discredited, many periodicities or quasi-periodicities are central to understanding the regulatory processes and dynamic mechanisms of change in both the atmosphere and oceans. Examples include contemporary modes of variability, such as El Niño southern oscillation (ENSO) phenomena (Diaz and Markgraf, 2000; Sarachik and Cane, 2010) and the North Atlantic oscillation (NAO) (Hurrell et al., 2003), and past episodic events/cycles under quite different boundary conditions, as exemplified by Heinrich events (Andrews, 1998) and Bond cycles (Alley, 1998).

Explicit consideration of the systems concept began in the context of the investigation of the interaction of ecological communities with their environment, which led to the first use of the term ‘ecosystem’ in the 1930s (Tansley, 1935). However, later development of a distinct ecosystems approach was of greater significance to Earth system science than the term itself. The ecosystem approach to ecology emphasised energy flow and mineral cycling and may be seen as the predecessor of general systems theory (von Bertalanffy, 1951), environmental systems analysis and the concept of biogeochemical cycles (Golley, 1993). The description and analysis of biogeochemical cycles up to global scale, in terms of reservoirs, fluxes, sources, sinks, budgets, couplings, feedbacks, regulation, equilibria and thresholds for change is perhaps the most novel aspect of Earth system science (Jacobson et al., 2000; Selley, 2005). Their extreme expression can be seen in the Gaia hypothesis, which envisages the Earth system as regulating its own environment to the extent that conditions within the geo-ecosphere are maintained within habitable limits (Lovelock, 2000, 2006).

Another major aspect of Earth system science is the important role of environmental monitoring. This has a relatively long history in the context of the instrumental measurement of air temperature, precipitation and pressure; the first thermometer was invented by Galileo in 1597. The major expansion of meteorological stations on land in the last half of the nineteenth century (Jones and

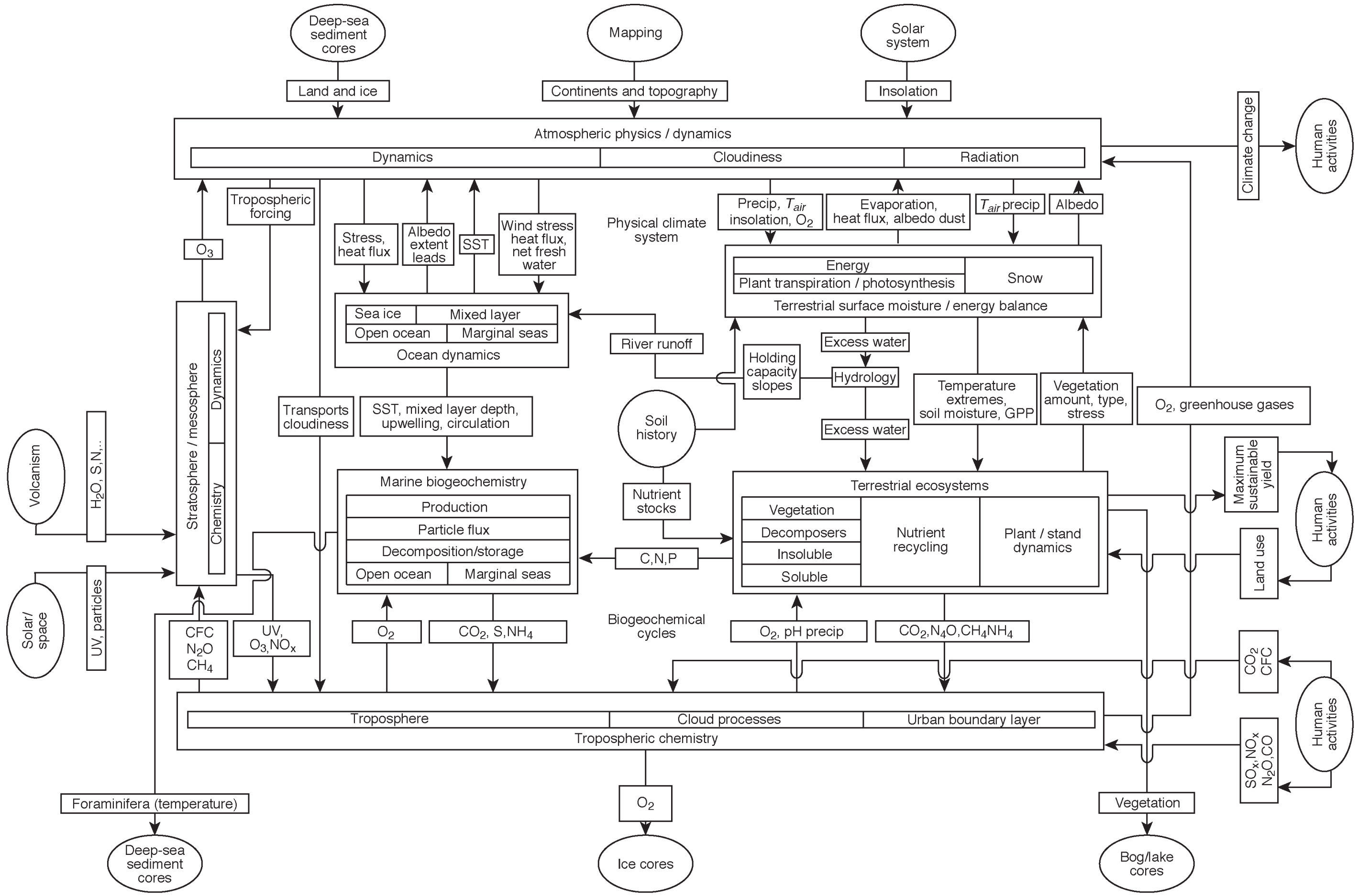


**Figure 1.4 A schematic representation of the key geo-ecological interactions involved in Earth system science.**

*Source*: Bretherton (1985) and Schellnhuber (1999).

Bradley, 1992) established the first world-wide environmental monitoring network. This was largely superseded after 1960 by satellite remote sensing over land and sea of variables associated with the radiation balance of the atmosphere, hydrometeorology, sea-surface conditions, the Earth's snow and ice cover, vegetation characteristics and soil properties (Anderson and Croft, 2009; Kidd et al., 2009; Quincey and Luckman, 2009; Wilson et al., 2001; see also Warner et al., 2009). Environmental monitoring has been instrumental in the detection of climate change and many other aspects of environmental change over the last few decades. The detection of the rising level of carbon dioxide ($CO_2$) in the atmosphere and its distinct seasonal pattern is a particularly important example (Keeling et al., 1995). Since the beginning of the twenty-first century alone, more than 100 satellite sensors have been launched (Boyd, 2009). The much longer-term perspective provided for Earth system science by palaeoenvironmental reconstruction clearly has an important complementary role (see later).

Similarly, from around the mid-twentieth century, systems analysis has complemented monitoring and provided the basis for the modelling approach to Earth system science (MacCracken, 2002). General circulation models (GCMs) hold a particularly important place in the development of Earth system science because they have been intimately associated with predicting future climate. The major shift in the focus of research on climatic change towards the future appears to have taken place around 1990 and to have been associated with the acceptance of the concept of anthropogenic global warming forced by greenhouse gases (Chambers and Brain, 2002). The earliest GCMs from the 1960s, which provided a three-dimensional, grid-based, time-evolving simulation of the atmosphere circulation (AGCMs) or the ocean circulation (OGCMs), based on dynamical equations governed by the laws of physics and a set of boundary conditions, have been improved upon in several different ways (Bartlein and Hostetler, 2004; IPCC, 2007a). Their initial and subsequent development has been highly dependent on parallel developments in computing, especially those associated with super computers.

The first coupled atmosphere-ocean models (CGCMs or AOGCMS) were developed in the 1990s. Currently, various other aspects of the Earth–atmosphere–ocean system, including sea ice, aerosols, the carbon cycle and the dynamics of vegetation are included in the most sophisticated GCMs. Other important current developments include the use of regional or limited-area models (LAMs), which are constrained and driven by the outputs from GCMs to enable higher spatial resolution at the regional scale, and the use of Earth-system models of intermediate complexity (EMICs), which focus on the processes important for the functioning of the geo-ecosphere as a whole while saving considerably on computer time (Claussen et al., 2002).

Numerical models are not only the most important tools available for making projections about future climate, but they are also necessary for formulating and testing hypotheses about the causal mechanisms that connect the events and processes of the geo-ecosphere (and indeed of any geo-ecosystem). By now, numerical models have been developed for virtually every process involved in environmental change, including the linkage of biophysical processes with the human drivers of change (Oldfield, 2005). Progress in Earth system science at the present time is highly dependent on the careful selection of different types of models, which provide a framework for inter-relating observations and cross-checking outcomes.

Monitoring and modelling of the global geo-ecosystem has generated a huge quantity of data, largely in digital form. This has stimulated and has been stimulated by the internationalisation of research, which includes not only the establishment of international research organisations and global data bases as already discussed, but also data dissemination via the Internet and the

World Wide Web and the archiving of data in the World Data Centre network. This international dimension is very characteristic of data collection, analysis and synthesis throughout Earth system science.

### 4.3 The development of sustainability science: understanding the dynamics of people-environment interaction with a view to a sustainable future

Sustainability science has been emerging as a subfield only since the 1990s (Clark and Dickson, 2003). In seeking to understand the dynamics of the interactions between people and their biophysical environment with a view to ensuring a sustainable future, it may be viewed as the reaction of scientists to the preponderantly societal and political processes that were shaping the sustainable development agenda in the 1980s (Kates et al., 2001). Hence, it can be regarded as the research and development branch of a practical agenda, which was defined by the World Commission on Environment and Development (WCED) – the Brundtland Commission – as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Sustainable development therefore implies an increase in wealth with due regard for the welfare of people in all parts of the world (intragenerational equity) and through time (intergenerational equity) while recognising the limitations on how this can be attained.

Sustainability science is, in many respects, the least well-developed aspect of the science of environmental change. Core questions involving the vulnerability and adaptability of society to and the impact of society on the biophysical environment lack an established theoretical framework. Many of the issues have been identified, but the necessary knowledge structuring, data coordination and multidisciplinary cooperation have yet to emerge (Kauffmann, 2009).

However, recognition of fundamental aspects of the interactions of nature and society can be followed back to at least the time of George Perkins Marsh, who recognised the devastating scale of human impacts on the landscapes of Europe, North Africa and Asia Minor in his book *Man and Nature, or Physical Geography as Modified by Human Action*, published in 1864. Concepts of conservation, protection, prevention, remediation, restoration, management and sustainability grew from such early observations and descriptions of the human impact, eventually affecting actions and policies ranging from local environmental management to global international conventions. The twentieth century development of soil conservation in the US, which culminated in the acceptance of a holistic, ecosystem-based concept of sustainable soil by the US Department of Agriculture (Berc, 2005), provides a good, specific example. Developments in theory and practice were triggered in particular by soil erosion problems and the establishment of the Dust Bowl in the North American Great Plains region.

The naïve and flawed geographical theories of climatic and environmental determinism, expounded in particular by Ellsworth Huntington (1924) and Ellen Churchill Semple (1935), saw environmental effects on human populations as simple, direct and causal. Although such views were rightly rejected, an unfortunate reaction was to ‘throw out the baby with the bathwater’. The result was that right through to the 1960s a trenchant retreat from all things climatic made it difficult to argue that climate and the biophysical environment more generally could be an important factor in human affairs. The early theories were replaced during the mid and late twentieth century by more sophisticated models, involving complex, indirect and reciprocal relationships. Examples of such models include those of technological materialism; cognitive behaviouralism; human, cultural and political ecology; and adaptive systems (Knight, 1992; Matthews and Herbert, 2004; Schutkowski, 2006). While these models brought improved understanding, none provided an all-embracing framework for research. Each contributing discipline – for example, ecology, geography, archaeology, anthropology and sociology – brought a subset of ideas and methods and a different perspective. Important scientific perspectives were introduced from ecology, especially through ecosystem concepts (as considered above in relation to Earth system science), and this influence continues to the present in contributions ranging from conceptualisation at the boundary between science and the humanities (Simmons, 1997) to formal modelling and computer simulation (Turchin, 2003).

Environmental archaeology (geo-archaeology), closely allied to Quaternary science, is important for its insights into the temporal dimension of the human past (Butzer, 2008; Rapp and Hill, 2006; Van der Leeuw and Redman, 2002). Scientific archaeology developed rapidly from the mid-twentieth century, applying and adapting biological, chemical, physical and computing techniques to archaeological sites and materials and greatly improving the evidence base (Bothwell and Higgs, 1963; Dincauze, 2000; Goldberg and Macphail, 2006). In contrast, the methods of cultural anthropology, like those of human geography, demonstrated the importance of the behavioural factors that are involved in any interpretation of human–environment interaction (Barnard, 2000; Crate and Nuttall, 2009; Johnston and Sidaway, 2004). Processual archaeology similarly stressed culture process, while post-processual archaeology takes further the importance of the cultural context and the difficulties for interpretation and theory arising from the possible different meanings that can be attributed to the material evidence (Hodder, 1985; Johnson, 1999).

A number of other disciplines have contributed, or have the potential to contribute, to understanding the human dimensions of environmental change and hence to sustainability science. In Figure 1.3, these are represented by environmental history, environmental economics, 'green' politics, and social science perspectives. Environmental historians contribute investigations of (1) the influence of environmental factors on human history; (2) the environmental changes caused by human actions (and the way these, in turn affect changes in society); and (3) the history of human thought about the environment, and the ways in which changing human attitudes have motivated actions that affect the environment (Hughes, 2006). Their contributions range from relatively narrow, 'scientific' reconstructions of past environments, such as the classic *Times of Feast, Times of Famine* by the French historian Emmanuel Le Roy Ladurie (1972), which concerns the history of climate, to expansive surveys of world history in relation to environment (e.g., Burke and Pomeranz, 2009; Richards, 2003), and a focus on the vulnerability of past societies, advocated by Pfister (2010) as a twenty-first century theme for historical climatology.

Social science perspectives include those of philosophy, politics, sociology, cultural anthropology, human geography, economics and law. These disciplines view environmental change in different ways but have all been influenced by the recent growth in scientific understanding of human impacts on nature and the increasing influence of 'green' politics, the latter driven by public concern over 'environmental issues' (Page and Proops, 2003). Social science perspectives have introduced concepts, such as resource limitation, the demographic transition, natural disasters, endangered species, the precautionary and polluter-pays principles, globalisation, sustainable development, sustainable cities, environmental security, and ecological modernisation in relation to environmental issues associated with consumption, population growth, biodiversity loss and global climate change.

Human impact on the geo-ecosphere, and how to deal with it, remains the enduring dominant theme in sustainability science. The ecological contribution is clearly central to current practices in sustainability science, which is struggling to embrace fully the social dimensions of environmental change (cf. Constanza et al., 2007; Scoones, 1999). Impacts, vulnerability to risk, adaptation and mitigation – to paraphrase the subtitles of the latest Reports of the Intergovernmental Panel on Climate Change (IPPC, 2007b, 2007c) – are the principle themes in sustainability science. The main methods employed are based on (1) environmental impact assessment, which seeks to identify the consequences of a particular event or stress, such as climate change, throughout a variety of social or geo-ecological systems; and (2) vulnerability assessment, which selects a particular system or group, such as Arctic ecosystems or Indian farmers, and seeks to determine the risk of adverse reactions to a range of stresses (Steffen et al., 2004; see also National Research Council, 2007, which has carried out a comparative analysis of several global change assessments including, amongst others, those of the Intergovernmental Panel on Climate Change, the United Nations Convention on Biological Diversity, the Arctic Climate Impact Assessment and the Millennium Ecosystem Assessment).

Adaptation and/or mitigation strategies are then designed to anticipate and avoid projected conditions, enhance resilience to change, reduce adverse effects and/or reduce the intensity of the drivers of change (Adger et al., 2009; Berkes et al., 2003; Gunderson and Holling, 2002; Kiehl, 2006; Wigley, 2006). A wide range of options are potential contributors to decarbonisation of the global economy. These include behavioural change, cap-and-trade regimes, carbon taxes, nuclear energy, renewable-energy technologies, carbon capture and storage, sequestration by forests, improving energy efficiency and geo-engineering (Helm and Hepburn, 2009; Launder and Thompson, 2009). One of the most important policy questions which, in the context of climate change impacts at least, has been largely avoided until now, is what combination of strategies can best reduce impacts (Parry, 2009). It must be emphasised, however, that sustainability science embraces not only global climate change and its impacts but also all local, regional or global environmental changes anywhere within the geo-ecosphere and their reciprocal interaction with people.

### 4.4 Towards an integrated science of environmental change

Rather than regarding the three strands as separate linear successions with distinct stages, we have attempted to suggest in Figure 1.3 a progressive expansion of the field. Development has occurred by the addition of new paradigms or milestones through time while retaining a legacy of older ones. This multidisciplinary field has also seen a rapid increase in its range of specialisations and the techniques they employ. Overall, the emphasis has moved from (1) curiosity-driven, inductive investigations of the past by individual scientists, to (2) deductive research often involving teams of workers cooperating at the national level, on to (3) projective modes of problem definition and research development coordinated by international organisations and dominated by what may happen in the future (Oldfield, 1993). The last phase is also influenced increasingly by government funding, public opinion and the media.

In many respects, Earth system science has an overarching role in relation to the triumvirate of subfields – Quaternary science, Earth system science and sustainability science – that are recognised in Figure 1.3. This is clear from the extent to which elements of Quaternary science and sustainability science are involved in Figure 1.4 and can be exemplified further by reference to the ‘outrageous’ Ruddiman hypothesis (Ruddiman, 2003, 2005, 2007; Ruddiman and Ellis, 2009). This disputed hypothesis, which has lead to some interesting research and is still evolving, suggests that anthropogenic effects on global climate due to changes in the concentration of greenhouse gases in the atmosphere were evident long before the burning of fossil fuels during the Industrial Revolution and were caused by the development of agriculture and associated land-cover and land-use changes, as early as 8,000 years ago (for $CO_2$) and 5,000 years ago (for methane). It is argued that these changes, in turn, affected other parts of the Earth system, such as the hydrological cycle and soil erosion at local and regional levels.

Over the next few decades, there is considerable scope for further interdisciplinary development (cf. Bhaskar et al., 2010). This requires the integration of concepts and approaches from the different disciplines and subfields, and the derivation of unified methodologies, theories and applications under an Earth systems science framework. This type of coming together is happening already in relation to the use of palaeoclimatic information to improve the accuracy of predictions about future global warming. Until the CLIMAP (Climate: Mapping, Analysis and Prediction) and COHMAP (Co-operative Holocene Mapping) projects (CLIMAP Project members, 1976; COHMAP Members, 1988), the empirical, field- and laboratory-based study of palaeoclimates was carried out largely independent of the theoretical modelling of the global climate by computer scientists. It is now clear, however, that the past is essential to understanding the likely future, because it extends the basis of our knowledge and thereby enhances our ability to make reliable predictions about the future. This is particularly important in relation to high-resolution palaeoclimatology, which has the potential to generate process knowledge incorporating climate variability on timescales of relevance to the concerns of society (Hughes and Ammann, 2009). Specifically, there are at least eight general grounds for investigating past environmental change in the context of possible futures. Specifically, palaeoenvironmental reconstructions provide:

- the long-term context for understanding environmental change as part of Earth's history;
- a base line for future projections;
- a means to quantifying the variability that occurs within the Earth system, and hence the uncertainty associated with future projections at a variety of spatial and temporal scales;
- identifiable trends that may be detected in the past and projected into the future;
- a wide range of past events relevant to developing general explanations of the drivers, processes and dynamics of change, and how the Earth's geo-ecosystems react to change;
- situations that are not analogous to those that exist on Earth at the present time but may occur in the future;
- evidence relevant to the attribution of change, the relative importance and combined effects of natural variability and human impacts; and
- data for the design, parameterisation and testing of models, such as GCMs, that are capable of making numerically based projections. (The same models are increasingly used, moreover, to test explanations for the environmental changes of the past.)

Some of these grounds were advocated by Battarbee (2008), McCarrroll (2010) and Snyder (2010) to justify, respectively, research into the variability of Holocene climate, for a change in the trajectory of Quaternary science towards high-resolution reconstruction of palaeoclimates over the last millennium or two, and for palaeoclimatic research in general. However, the eight reasons listed above have broader applicability to a wider range of timescales involved in environmental change research *sensu lato*.

Perhaps the greatest of the remaining challenges relates to the human dimensions of environmental change and, in particular, to the integration of scientific methodologies with those of the social sciences and humanities. Ways must be sought to incorporate further social and cultural perspectives into human–environmental systems models and scenario construction (de Vries, 2007). In some respects, such perspectives have barely progressed beyond the conceptual model stage (Beddoe et al., 2009; Hornborg and Crumley, 2007; Janssen, 2002; Liverman and Cuesta, 2008; Liverman et al., 1998; Machlis et al., 1997; O'Sullivan, 2008; Rotmans, 1998).

According to E.O. Wilson, the greatest enterprise of the mind has always been and will always be the attempted linkage of the sciences and the humanities, which he has termed 'consilience' between what C.P. Snow described as the 'Two Cultures' (Snow, 1998; Wilson, 1998). In the field of environmental change there is both a need and an opportunity for this consilience to occur (see also Crumley, 2007; Oldfield, 2007).

## 5 ORGANISATION AND CONTENT OF THE HANDBOOK

Following on from this introductory chapter, which provides essential background with an emphasis on the development of the science of environmental change, comprehensive coverage of the present state of the field is accomplished by a further 43 chapters organised into six sections:

1. Approaches to Understanding Environmental Change
2. Evidence of Environmental Change and the Geo-ecological Response
3. Causes, Mechanisms and Dynamics of Environmental Change
4. Human-induced Environmental Changes and Their Impacts on Geo-ecosystems
5. Patterns, Processes and Impacts of Environmental Change at the Regional Scale
6. Past, Present and Future Responses of People to Environmental Change

The first three sections comprise Volume 1, which is subtitled 'Approaches, Evidence and Causes', while the last three sections constitute Volume 2, the subtitle of which is 'Human Impacts and Responses'.

### *5.1 Approaches to understanding environmental change*

The first section critically examines the philosophical and methodological basis of research in this field. All six chapters are broad and inclusive 'background' chapters that are closely linked to the more specialised chapters in later sections.

In Chapter 2, Stephan Harrison covers *philosophical and methodological perspectives on the science of environmental change*. He considers how scientific method is applied in the investigation of environmental change. Particular reference is paid to palaeoenvironmental reconstruction and modelling, including the practical and theoretical restrictions imposed by palaeoenvironmental data, model uncertainty, reductionism and emergence, equifinality, pattern recognition and uniformitarianism.

Chapter 3, written by Keith Alverson, covers *direct observation and monitoring of climate and related environmental change.* This includes observation and monitoring of many aspects of atmospheric, terrestrial and marine environments, from early weather records to satellite remote sensing. The chapter focuses on global monitoring of the various components of the Earth system, and the importance and limitations of current monitoring programs in relation to Earth system science.

*Reconstructing and inferring past environmental change,* the theme of Chapter 4 by Frank Chambers, covers approaches involving the reconstruction of proxy records of past environmental change from natural archives. Philosophical principles, techniques and methods are assessed in relation to the full range of natural archives while peat bogs are used for a detailed case study. Particular problems discussed include the limitations of proxy data, supposed global and hemispheric records, quantification of rates of environmental change, the use of palaeoecological data for climate projections, possible over-interpretation, hyperbole and bias and, lastly, some aspects of contested science.

Chapter 5, *Dating environmental change and constructing chronologies*, by Mike Walker, describes the various dating techniques that are now employed to support environmental reconstructions by developing a temporal framework for Quaternary events.

It covers the full range of available dating techniques, which are broadly classified into radiometric dating, radiation exposure dating, incremental dating, relative dating and methods for establishing age equivalence. While discussing the principles, limitations and application of each method, the general topics covered include precision and accuracy, reduction of uncertainty, Bayesian techniques, event chronostratigraphy, tuning and age modelling.

*Modelling environmental change and developing future projections* is the topic of Chapter 6 by Reto Knutti. Different generic types of numerical models, including simple models, GCMs, regional models, and Earth system models of intermediate complexity are evaluated. Particular attention is given to climate models and the fundamental role of palaeoenvironmental data in testing models and the mechanisms underlying climate change. Computational capability and knowledge of environmental processes are viewed as jointly limiting possible progress in bridging the gap between numerical weather prediction and long-term climate projection. Current models are seen not only as still a long way from delivering what studies of local adaptations require but also as more difficult to improve as the target is approached.

The last chapter of this section, Chapter 7, includes *approaches to understanding long-term human–environmental interaction – past, present and future*. In this chapter, John Dearing covers the distinctive methodologies and problems associated with investigating the changing nature of interactions between people and their environment. Global- to regional-scale human impacts and societal collapse are reviewed with particular reference to the importance of an Earth system perspective and in terms of complex human-environmental systems. Detailed consideration is given to complex system behaviour, natural *versus* human-induced variability, thresholds and alternative steady states, and trends and trajectories. Attention then focuses on anticipating the future: establishing baseline conditions for restoration and management targets, the problem of regional integration of long-term records in regions and landscapes, the usefulness of resilience theory and the adaptive cycle, and the potential of simulation modelling.

## 5.2 Evidence of environmental change and the geo-ecological response

The nine chapters of Section II are concerned with the nature, advantages and limitations of the various sources of evidence of environmental change. These chapters also include evidence of the impact of environmental change on the various (natural) geo-ecological systems, and of the response of these systems. Emphasis is given, where available, to high-resolution evidence of global change from observational and/or proxy sources. This evidence includes, but is not confined to, the responses of the different systems to climate change and global warming (which is also specifically covered in Section IV).

This section begins with Chapter 8 on *environmental change in the geological record* by Jane Francis, Alan Haywood, Daniel Hill, Paul Markwick and Claire McDonald. Their theme supplies the long-term perspective on environmental change focusing on the importance of the deep past for understanding Quaternary environmental change and including an overview of the methods used, which range from environmental reconstruction to modelling. Examples of lithological, geochemical and fossil evidence of change from the geological record are presented and the major changes in climate experienced by planet Earth over the last 500 million years are summarised.

In Chapter 9, Ian D. Goodwin and William R. Howard focus on the *evidence of environmental change from the marine realm*, covering a wide range of proxies – from deep-sea sediments, coral reefs and continental margins – including an assessment of their prospects for projecting marine and coastal change into the future. Deep-sea sediments provide information on Pleistocene sea levels, sea-surface temperatures, sea-ice cover, deep-ocean circulation, the ocean carbonate cycle, ocean biotic changes and terrigenous dust flux. Detailed consideration is given to coral reefs as a source of information on eustatic sea-level change, and surface ocean temperature, salinity and circulation changes using, for example, coral isotope, geochemical and calcification proxies. Sediments from continental margins contribute information on changes of sea level, coastline sediment budgets, wave climate, storm surges and tsunami history.

*Evidence of environmental change from the cryosphere* is considered in Chapter 10 by Shawn Marshall. After an introductory survey of the nature and extent of the global cryosphere, its present state is assessed in the light of Holocene climatic variability and possible future changes. Particular attention is given to the observational record, including evidence from mountain glaciers, the Greenland and Antarctic ice sheets, sea ice, seasonal snow cover, river and lake ice, and permafrost. Ecological impacts of recent changes, the climatic feedbacks of cryospheric change and the outlook for the cryosphere are all considered in some detail.

Chapter 11, by Wim Hoek, covers *evidence of environmental change from terrestrial palaeohydrology*. Evidence of palaeohydrological processes from geomorphological, sedimentological, lithological, isotopic, geochemical and biological sources are evaluated. The nature of environmental change in the palaeohydrological record is then considered in relation to precipitation, evaporation, drought, river discharge, sediment load and flood frequency. Environmental reconstruction involving lakes, rivers and groundwater are examined in most detail, highlighting studies of cut-and-fill history from river terraces and Holocene lake-level change, before concluding with a brief survey of some recent developments.

Alison Smith (Chapter 12) covers the *evidence of environmental change from terrestrial and freshwater palaeoecology*. She begins by focusing on the evidence from biological proxies ranging from microfossils to macrofossils and from pollen, testate amoebae, diatoms and charcoal to ostracods, molluscs, chironomids, beetles and vertebrates. Problems of calibration and nonanalogue assemblages are assessed and resonances between subfields and with other fields are discussed with particular reference to refugia, trophic structure, abrupt climate change and interactions between groundwater and surface water. Finally, important new developments involving biogeochemistry, ancient DNA and phylogeography are identified.

Chapter 13, by Joe Mason, *on evidence of environmental change from aeolian and hillslope sediments and other terrestrial sources,* considers loess, palaeosols, aeolian sand, colluvial deposits, cave sediments and borehole temperatures. Several problems of interpretation are highlighted, especially the limited evidence that may be preserved relating to complex geomorphic and pedogenic processes, and the difficulties in dating what is often a discontinuous record. However, excellent examples are provided of how each of these sources can contribute unique insights into environmental change in specific environments.

*Environmental change and archaeological evidence* is the topic of Chapter 14 by Tim Denham. The emphasis here is on archaeological evidence for establishing associations between the environment and people in the prehistoric past. After defining the subdiscipline of environmental archaeology, the characteristics of human–environmental interactions, the types of site and the types of data investigated in the context of environmental archaeology are introduced. Proxy records frequently used by archaeologists on- and off-site for palaeoecological reconstruction (including charcoal, pollen, phytoliths, diatoms, starch granules, wood, dendrochronology and seeds) are then outlined. The distinctive subfields of geoarchaeology, archaeobotany and archaeozoology are discussed in more detail. Detailed case studies are included to illustrate the principles of environmental archaeology, including the history of settlement in the Sahara and multi-proxy reconstruction in the highlands of New Guinea.

In Chapter 15, Eugene Wall and David Frank cover the *evidence of environmental change from annually resolved proxies with particular reference to dendroclimatology and the last millennium.* The chapter focuses on the search for a robust, high-resolution record of climate change at global and hemispherical scales, and the central role of dendroclimatology in this search. The so-called 'hockey-stick' curve and related efforts to reconstruct the temperature variations over the last millennium, including the different methods used, are fully discussed. Detailed attention is given to the transition from the 'Medieval Climate Anomaly' into the 'Little Ice Age', including both the global climate patterns associated with this transition and their potential causes. Despite the technical limitations, it is concluded that it will be possible to produce more accurate estimates of past temperature variations and use these in making more accurate predictions of future temperatures.

The final chapter of Section II, written by Cary Mock, covers *early-instrumental and documentary evidence of environmental change* and focuses on palaeoclimatology during the historical period. An overview of historical climate sources is provided, including noninstrumental evidence from newspapers, government records, annals and chronicles, private diaries and explorers' accounts, and ship logbooks. Methodological issues, such as their reliability and their use in regional and synoptic reconstructions are discussed and some emerging future directions of study are identified.

### *5.3 Causes, mechanisms and dynamics of environmental change*

Section III critically assesses the nature and importance of the various natural and human agencies that interact to produce environmental changes, especially changes in climate. Eight chapters cover external forcing factors, autovariation within the Earth–ocean–atmosphere system (i.e., internal mechanisms and feedback processes), interaction between forcing factors at various timescales, and the climatic and anthropogenic drivers of change in the global geo-ecosystem.

The first chapter in this section, Chapter 17, by Paul Bishop covers *plate tectonics, continental drift, vulcanism and mountain building*. This complements Chapter 8 in that it covers the 'deeper-Earth' geological processes that contribute to environmental change, including long-term effects on landscape evolution conditioned by reciprocal interactions between plate convergence, uplift, climate and erosion over very long timescales. Several different hypotheses have been proposed, which are tested against evidence from the geological record and by modelling exercises. The environmental effects of volcanic eruptions are also considered, including short- and long-term effects on ocean temperatures, sea level and ocean circulation.

In the *extraterrestrial causes of environmental catastrophes* (Chapter 18), Elisabetta Pierazzo and Jay Melosh provide an overview of the environmental effects of extraterrestrial impact events. They first assess the impact hazard from past impact rates on the Earth and the Moon. This is followed by a summary of the impact cratering process, the propagation of shock waves in the terrestrial and marine environment as earthquakes and tsunami, the air-launch of ejecta, and thermal effects. Longer-term perturbations to the dust and greenhouse-gas loading of the upper atmosphere, the response of the Earth system to large impacts and, lastly, the environmental impact effects that are favourable to life, are also evaluated.

In Chapter 19, André Berger elucidates *astronomical theory and orbital forcing*. This theory provides a basis for understanding the primary climatic cause of the periodic alternation of glacials and interglacials throughout the Quaternary based on regular variations in the Earth's orbit around the Sun. After an historical overview of the important stages in its development, the concepts and mathematics of the theory are elucidated. Most of the chapter deals with the calculation of astronomical forcing of climate, explaining both the long-term variations in eccentricity, obliquity and precession and their impacts on insolation. The conclusion highlights related unanswered questions.

Moving on to shorter timescales, Siwan Davies and Anders Svensson review, in *millennial-scale climatic events during the last glacial episode* (Chapter 20), the contrasting signals and environmental impacts of millennial-scale climatic events, their timing and degree of synchronicity in different geographical regions, and the mechanisms proposed to account for these instabilities. These abrupt perturbations are important examples of when the Earth's climate is forced across thresholds. They are therefore fundamental to understanding the dynamics of past climates and for informing models that make projections of future climate. The chapter focuses on the uncertainties in our knowledge of the rate, timing, amplification and forcing mechanisms driving such short-term climatic variability. Particular attention is given to the thermohaline circulation of the ocean and changes in tropical climate as potential forcing mechanisms.

Chapter 21, by Raimund Muscheler and Erich Fischer, covers *solar and volcanic forcing of decadal- to millennial-scale climatic variations*. These are two important sub-Milankovitch forcing factors that are implicated, both individually and in combination, as possible causes of climatic variations. The focus is on past records of these factors, which are especially useful because these forcings exhibited a larger range of variability in the past and their influence can be disentangled more easily in the absence of anthropogenic effects. There is continuing controversy about the relative and absolute importance of both solar and volcanic forcing. Although most studies see only a limited role for solar forcing of global temperatures, possible amplifying factors are poorly known. Volcanic forcing has relatively short-lived effects but the potential effects of mega-eruptions and temporal clustering of major eruptions need further investigation.

In Chapter 22, Mathias Vuille and René Garreaud focus on *ocean–atmosphere interaction on interannual to decadal timescales*. This involves detailed consideration of the coupling of the ocean and atmosphere and its influence on climatic variability. ENSO phenomena, the Pacific decadal oscillation (PDO), the North Atlantic oscillation (NAO), and the northern and southern annular modes (NAM and SAM) are considered in detail, while tropical Atlantic variability (TAV) and the Indian Ocean dipole (IOD) are also covered. The physical processes associated with these oscillatory modes, which result from the different scales of variability involved in the atmosphere and ocean, are discussed. The main emphasis is on characterising the spatiotemporal variability of these modes, their dynamic behavior and their potential for prediction as many are of high societal relevance with significant impacts on natural and human systems.

Chapter 23, by Thomas Pedersen and Rainer Zahn, presents an overview of the *responses of biogeochemical cycles in the sea to environmental change* at various time scales with special focus on high-frequency variability of key nutrient cycles, particularly during the last ice age, and their coupling to ocean physics. Emphasis is placed on the N, Fe and P cycles and their interaction with photosynthetic production and oxygen concentrations in the sea. The chapter also explores the uniformitarianist view that understanding the past can shed light on the present and possibly the future. This includes the expansion of so-called low-oxygen 'dead zones' in intermediate waters on continental margins, declining oxygen levels in the deep waters in some marginal seas, and changes in primary production and $CO_2$ uptake in the open ocean as a consequence of warming, increased stratification, and varying nutrient fluxes.

In the last chapter of this section (Chapter 24), the *anthropogenic drivers of environmental change,* are examined by Jemma Gornall, Andrew Wiltshire and Richard Betts. This chapter details the indirect and direct anthropogenic drivers of environmental change and highlights the intrinsic links that exist between them. The indirect drivers include those attributed to demographic, economic, sociopolitical, cultural, scientific and technological factors. The direct drivers of environmental change include climate, land-use and land management. Both past and future trends in development of such drivers are identified and the causes of change are assessed. Case studies of, for example, Indian agriculture, coral reefs and Amazonian deforestation are used to illustrate the environmental impact of each driver and, where possible, link these to other causal factors.

## 5.4 Human-induced environmental changes and their impacts on geo-ecosystems

Volume 2 begins with the five chapters of Section IV. These chapters focus mainly on the effects of human activities on Earth–atmosphere–ocean systems, the increasing scale of the human impact through time (especially during the Anthropocene) and the many linkages involved in interactions between people and their biophysical environment.

The section begins with an analysis and discussion of key aspects of the *monitoring of global land-cover* by Sietse O. Los and Jamie Williams (Chapter 25). Monitoring of land-surface vegetation is important for several reasons: it provides estimates of biodiversity and how it may change over time; it provides information on the impact of climate events (such as droughts or warmer springs) on vegetation growth; and it provides data for input to models used to understand the global carbon cycle, the water cycle, and the energy budget. This chapter provides an overview of the methods used to assemble the land-surface vegetation data and related information on surface water, rock and soil. Particular attention is paid to global land-cover classifications assembled from inventories and the monitoring of biophysical parameters from satellite observations.

Chapter 26, by Craig Miller and Iain Gordon, which covers *human impacts on terrestrial biota and ecosystems*, consider the impact of humans on biodiversity and ecosystem services through a socioecological system lens. They seek to advance the Millennium Ecosystem Assessment's (MEA) premise that human-modified ecosystems are losing or have lost the capacity to provide essential ecosystem services and they identify a potential path forwards. Their general message is to remind environmental scientists, in the face of a somewhat depressing outlook, of the unmet challenge to move beyond a research agenda and provide interdisciplinary solutions (involving biophysical, socioeconomic and institutional actions) for restoring and sustaining the ecosystem services provided by nature.

In *human impacts on lacustrine ecosystems* (Chapter 27), Rick Battarbee, Helen Bennion, Neil Rose and Peter Gell identify and disentangle the roles of different kinds of human activity on lake ecosystems based on evidence from both sediment records and long-term monitoring. They consider how lake ecosystems have been altered with respect to cultural eutrophication, acidification, salinisation and contamination by toxic substances. Lake status at the present day is compared with the reference conditions that pertained prior to the main impact of human activity. In each case, the key processes are outlined, possible remedial action is discussed and problems for the future are considered, especially with regards to the potential impact of climate change.

*Human impacts on coastal and marine geo-ecosystems* are discussed by Ben Daley in Chapter 28. While covering the full range of human impacts on coastal and marine environments and ecosystems, some recurring themes are highlighted: the unsustainable exploitation of coastal and marine resources (with particular emphasis on large marine animals and fishes); coastal and marine pollution; effects of climate change on coasts and seas; and the effects of coastline change. Each type of impact represents a major threat to the integrity of coastal and marine systems for various reasons, including: the alarming rate of decline of marine biodiversity; the creation of 'dead zones' in coastal waters as a result of eutrophication; and the changes in sea-surface temperature (SST), sea-surface salinity (SSS), sea levels, ocean currents, ocean acidity and ecosystems that are occurring as a result of climate change. The chapter draws on studies from the literatures of environmental science and environmental history, and points to the urgent need to enact effective international conservation measures for coastal and marine environments that are based on the principles of adaptive management.

The last chapter in Section IV, Chapter 29, written by Kevin Noone, covers *human impacts on the atmosphere*. Four 'snapshots' in time between ancient Greece at ca 400 BC and London, England, in AD 1661 are used to demonstrate that (1) humans have made impacts on the atmosphere for much of recorded history and (2) air pollution has long been connected with other adverse effects on humans and ecosystems. Changes in $CO_2$ and ozone concentrations in the atmosphere are then used to demonstrate the increasing magnitude and global scale of the human impact during the Anthropocene. This is followed by further detailed consideration of spatial variation in the impact from trace gases and aerosols, examples of the interconnections and effects of atmospheric pollutants in relation to ocean acidification and aerosols, and the general need for better coordination between policies related, on the one hand, to air pollution and, on the other, to climate change.

### 5.5 Patterns, processes and impacts of environmental change at the regional scale

Chapters 30–37 in Section V evaluate environmental change at the regional level. The eight major regions represent the main geo-ecosystems of the Earth at the scale of the major biomes. Although the emphasis given in each chapter to particular continents or timescales varies, each focuses upon distinctive regional characteristics and their relevance to research problems and issues.

*Environmental change in the humid tropics and monsoon regions* are covered by Mark B. Bush and William D. Gosling (Chapter 30). Research over the past decades has shown that climate changes at high latitudes cannot simply be extrapolated to low latitudes and that the tropics play an important role in global climate change. With reference to environmental changes since the Last Glacial Maximum, ranging from climatic variability driven largely by precipitation changes to megafaunal extinctions, the authors demonstrate this two-way influence. They also point out the different responses to given forcings that characterised the different continents, the broadly antiphase response of shifts in the major ecotonal boundaries that occurred in the northern and southern hemispheres, and the unique characteristics of the Holocene with its uniform reduction in landscape and biotic diversity.

In Chapter 31, Yang Xiaoping covers environmental change in the *arid and semi-arid regions.* He provides a global view with the aim of developing a coherent hypothesis about environmental changes that have occurred in the major drylands since the late Pleistocene. Detailed systematic attention is given to the direct evidence of environmental change – including the geomorphologic, sedimentologic, hydrologic, geochemical and biological records – available from the arid regions of Africa, Asia, the Americas and Australia. This leads onto a discussion of human impacts on drylands, land-use change and desertification, and the global impacts (particularly as a source of dust) of current environmental changes in these regions.

Mira Matthews takes a different approach in Chapter 32. She focuses on *environmental change in the Mediterranean Basin*, by far the largest of the regions of the Earth with a Mediterranean-type climate. She views the Mediterranean region as a bridge between the Atlantic Ocean and the Mediterranean Sea and recognises distinct differences between the Western and Eastern Mediterranean. Regional differences in palaeoclimate are examined with reference to marine and terrestrial (lake and speleothem) records. Detailed consideration is given to sapropel layers deposited in the Mediterranean Sea during the last 250 ka and to the evidence from speleothems for Holocene environmental change. The latter indicate rapid climate change events that are related to the archaeological record of cultural change.

In Chapter 33, Matt McGlone, Jamie Wood and Patrick J. Bartlein cover *environmental change in temperate forested regions* of the northern and southern hemispheres. Their review concentrates mainly on the history of temperate forests in relation to climatic forcing during glacials and interglacials, at the Last Glacial Maximum, during the Late Glacial, and throughout the Holocene. All seven regions dealt with in this chapter have followed strikingly similar trajectories driven primarily by Quaternary climate changes. However, the effects and interactions of geomorphic change, soils, fire, disease, insect attacks, megafaunal extinction, and the impact of humans also had major effects and are discussed largely from the viewpoint of their importance for forested ecosystems.

In Chapter 34, Pavel E. Tarasov, John W. Williams, Jed O. Kaplan, Hermann Österle, Tatiana V. Kuznetsova and Mayke Wagner take a broadly similar palaeoecological approach to *environmental change in the temperate grasslands and steppe*, focusing on the zonal temperate grasslands of the northern hemisphere. They review the environmental history of temperate grasslands based on the evidence from sedimentary records, lakes, mires and soils, combined with higher-resolution ecological, historical and instrumental records. To investigate changes in the global distribution of temperate grasslands on glacial–interglacial timescales, they used the BIOME4 global vegetation model driven by a series of GCM paleoclimate scenarios. The main changes on centennial to orbital timescales are viewed as driven by hydrological variability with complicating effects from the activities of human activities and herbivore populations.

Chapter 35, by Marianne S.V. Douglas, deals with *environmental change in the Arctic and Antarctic* during the Anthropocene. She provides an overview of the geographic Arctic and Antarctic and then a general review of polar environmental change. She shows that despite being amongst the most remote and extreme environments on Earth, the polar regions are both dynamic and susceptible to anthropogenic impacts. Indeed, in respect of climate change and associated environmental changes, polar amplification means that these regions can be regarded as key to the early detection of global warming effects in terrestrial, freshwater and marine ecosystems. Effects of contaminants, such as persistent organic pollutants (POPs) and stratospheric ozone, are also considered in detail. The chapter concludes with an outline of the way science is organised in the circumpolar regions, some future needs, and the importance of environmental change in the Arctic to northern peoples.

Martin Beniston's approach in Chapter 35 on *environmental change in mountain regions* also places greatest emphasis on recent and future changes, especially those involving anthropogenic drivers. After considering why mountain regions are important for humankind, he briefly reviews how mountain environments evolved in the past, prior to advent of accelerated change through direct anthropogenic activities. The chapter then reviews some of the natural and human drivers of environmental change in mountains, including climate change, acid deposition, deforestation, and land-use and socioeconomic change. Possible future environmental change and its impacts on natural systems (involving snow and ice, hydrology, vegetation and fire hazard), and on managed systems are also discussed in some detail. Finally, the chapter assesses cross-cutting issues and possible adaptation and mitigation strategies.

*Environmental change in coastal areas and islands* by Patrick Nunn (Chapter 37) is the final regional chapter. These regions, which exhibit considerable environmental diversity and often possess dense human populations, are characterised by some unique environmental changes and problems and are particularly susceptible to sea-level change. Non-human causes and effects of both low-magnitude sea-level changes and abrupt and extreme events (involving sea level, climate, tectonics, and volcanic activity) are first considered. This is followed by a review of approaches to understanding environmental histories of coastal areas and islands, including the special problems and opportunities in relation to barrier coasts, coral-reef coasts and atoll islands. Recent human impacts are then discussed and the chapter concludes with an assessment of future prospects for these regions.

## 5.6 Past present and future responses of people to environmental change

The seven chapters of Section VI are devoted to the human dimensions of environmental change, the implications of environmental change for society and, especially, the responses of people to environmental change in the past, present and future. These chapters range in terms of their temporal depth from the evolution of the human species in the geological past to the actual and potential responses of those in developed and developing countries today and in the future. The first three chapters of the section focus on the past.

In *testing the role of climate change in human evolution* (Chapter 38) S.P.E. Blockley, Ian Candy and S.M. Blockley take the long view of the environmental interactions of both early hominids and anatomically modern humans (AMH). This chapter focuses on the role of environmental change in the origin, dispersal and extinction of hominids and on the scientific debates into the role of climate on the evolutionary history of our species. The problem of identifying the appropriate environmental evidence and directly tying in the hominid and archaeological evidence is highlighted. Discussion covers the last 4.4 million years, beginning with the earliest well dated Pliocene hominid *Adipiticus ramidus*, and the ongoing attempts to understand the role of climatic change on the complex evolutionary pattern of the early hominid apes, the gracile australopithicines, the more robust paranthropines, and the first members of the genus *Homo.* At the end of the mid Palaeolithic, the focus is on testing the role of abrupt climate change in the replacement of archaic hominids by AMH.

In *the origins and spread of early agriculture and domestication: environmental and cultural considerations* (Chapter 39), Deborah M. Pearsall and Peter W. Stahl discuss the process of domestication and approaches for identifying it, the geography and timing of early agriculture around the world and the explanations offered for its adoption, including the role of environmental change in its origin and spread. They address the fundamental questions of what is agriculture, what characteristics did humans seek in the plants and animals they domesticated, why did humans become agricultural, and what role might environmental change have played in adoption of an agricultural lifestyle, particularly as its earliest manifestations appear at a time of major climate change?

In Chapter 40, Georgina Endfield considers *complexity, causality and collapse: social discontinuity in history and prehistory*. Her purpose is to explore various examples of societal collapse and social discontinuity in global history and prehistory, but in so doing to highlight the importance of complexity and context in understanding collapse scenarios. It is argued that in order to understand any scenario of collapse, it is important to acknowledge a society's relative vulnerability to its specific social, cultural, demographic and political context, which changes over time. Numerous examples show that the cause of discontinuity or collapse was often a combination of events or the result of cumulative developments acting in particular circumstances. It is also demonstrated that environmental changes can trigger adaptation and development of civilisations. Considering a society's adaptive capacity at any point in time is therefore critical to understanding its propensity for collapse.

In the last four chapters of this final section, the emphasis moves explicitly to modern societies. First, Donald Nelson, in Chapter 41, covers the *vulnerability and resilience of contemporary societies to environmental change*. He describes the different intellectual histories of the concepts of vulnerability and resilience: the former focusing on a particular group to assess risk in relation to multiple and interacting environmental stresses; and the latter emphasising the underlying processes of change at the system level. This is followed by a discussion of (1) the ways in which the two areas are being brought to bear on each other within studies of adaptation to environmental change; and (2) the significant challenges that remain to be explored, such as relatively ineffective understanding of the functional links between ecological and social systems across scales and the implications of resilience and vulnerability research for effective policy. Finally, this author highlights some of the future areas of work in vulnerability and resilience studies necessary to identify pathways for the long-term viability of human populations.

In Chapter 42, Matthew Baylis and Andrew P. Morse discuss *disease, human and animal health, and environmental change.* Many diseases, whether vector-borne, water-borne, food-borne or directly transmitted, have known links to climate in terms of their spatial distribution, temporal occurrence or incidence and severity. As the world's climate changes, it is likely that at least some of these diseases, especially vector-borne and water-borne infections, will respond in some way. The nature of the response will depend on how climate affects the pathogens, hosts, vectors and transmission dynamics of a disease; on the rate, scale and nature of climate change; and also on the relative importance of climate drivers to other drivers of disease, which also change. Examples are provided of diseases that have already responded to climate change, most notably bluetongue, a viral disease of livestock which has spread across much of Europe in the last decade. By contrast, the impact of climate change on total malaria burden remains unclear with a wide spectrum of views depending on various weightings of importance of climate change to historical, recent and future projected changes in malaria distribution.

Chapter 43, by Katie Moon and Chris Cocklin, covers *mitigation of the drivers and effects of environmental change*; that is, the development and implementation of new or improved technologies to reduce the extent of human-induced environmental change. In relation to mitigation policy, they deal with policy instruments and the challenges of policy formulation in an international context, relationships between mitigation and adaptation, and the principles of uncertainty, precaution and equity. The strategy of mitigation programs, mitigation technology options and barriers, are then examined, the latter including barriers to the development, deployment and diffusion of new technology. Finally the actions involved in mitigation planning – abatement, carbon sequestration and biosequestration, and geo-engineering – are outlined and evaluated. Policy, program and plan formulation are considered in relation to the complexity and uncertainty of natural and social systems with a view to maximising their synergies.

In the last chapter of the section and of the book (Chapter 44) Chris Barrow takes a broad look at *socioenvironmental adaptation to environmental change: towards* *sustainable development*. Given the complex chains of causation involved in vulnerability, resilience, adaptation, mitigation and sustainability, he argues that this area of the study of environmental change can never be a wholly reliable science (or art). Nevertheless, an attempt is made to define and analyse the various links involved, possible responses to threats and opportunities, and how policies and actions might evolve to address future environmental changes. He further argues that a key to future success is for planners and administrators to be alert to sudden challenges, to be flexible, to seek vulnerability reduction, and not to focus only on human-induced global warming. Finally, he suggests that much of what is currently being done in the name of sustainable development is inflexible, lacking in diversity and is itself vulnerable. Hence, sustainable development may, paradoxically, sometimes hinder adaptation, proactive vulnerability reduction and appropriate mitigation measures.

## 6 CONCLUSION

This Handbook provides a comprehensive survey of the interdisciplinary science of environmental change that not only summarises the present state of knowledge in the field but also adds-up to more than the sum of its parts. In the introductory chapter we have tried to provide a framework for understanding the science of environmental change, particularly in terms of where it has come from and where it is heading. Subsequent chapters (which have also been briefly outlined in this chapter) provide much more detail on specific aspects and should enable academics, students and professionals to gain insights into both the substantive research achievements and the innovative work being carried out at the frontiers of the field. We also hope that the Handbook as a whole will be an inspiration to the scientists working in this field to do more for the benefit of science and society by viewing their specialities in the broader context.

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