1 Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction

Olav Slaymaker, Thomas Spencer and Simon Dadson

1.1 The context

Whatever one's views, it cannot be doubted that there is a pressing need to respond to the social, economic and intellectual challenges of global environmental change. Much of the debate on these issues has been crystallised around the activities of the IPCC (Intergovernmental Panel on Climate Change). The IPCC process was set up in 1988, a joint initiative between the World Meteorological Organization and the United Nations Environment Programme. The IPCC's First Assessment Report was published in 1990 and thereafter, the Second (1996), the Third (2001) and the Fourth Assessment Report (2007) have appeared at regular intervals. Each succeeding assessment has become more confident in its conclusions.

The conclusions of the Fourth Assessment can be summarised as follows:

(a) warming of the climate system is unequivocal;
(b) the globally averaged net effect of human activities since AD 1750 has been one of warming (with high level of confidence);
(c) palaeoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years;
(d) most of the observed increase in globally averaged temperature since the mid twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations; and
(e) continued greenhouse gas emissions at or above current rates will cause further warming and induce many changes in the global climate system during the twenty-first century that would very likely be larger than those observed in the twentieth century. Details of the methodology used to reach these conclusions can be found in Appendix 1.1.

The IPCC assessments have been complemented by a number of comparable large-scale exercises, such as the UNEP GEO-4 Assessment (Appendix 1.2) and the Millennium Ecosystem Assessment (Appendix 1.3) and, for example, at a more focussed level, the Land Use and Land Cover Change (LUCC) Project (Appendix 1.4) and the World Heritage List (Appendix 1.5). There is no doubting the effort, value and significance of these enormous research programmes into global environmental change (Millennium Ecosystem Assessment, 2005; Lambin and Geist, 2006).

1.1.1 Defining landscape and appropriate temporal and spatial scales for the analysis of landscape

It is important to establish an appropriate unit of study against which to assess the impacts of global environmental change in the twenty-first century and to identify those scales, both temporal and spatial, over which meaningful, measurable change takes place within such a unit. The unit of study chosen here is that of the landscape. There are strong historical precedents for such a choice. Alexander von Humboldt's definition of 'Landschaft' is the 'Totalcharakter einer Erdgegend' (Humboldt, 1845–1862). Literally this means the total character of a region of the Earth which includes landforms, vegetation, fields and buildings. Consistent with Humboldt's discussion, we propose a definition of landscape as 'an intermediate scale region, comprising landforms and landform assemblages, ecosystems and anthropogenically modified land'.

The preferred range of spatial scales is 1–100 000 km^2 (Fig. 1.1). Such a range, of six orders of magnitude, is valuable in two main ways:

(a) individual landforms are thereby excluded from consideration; and

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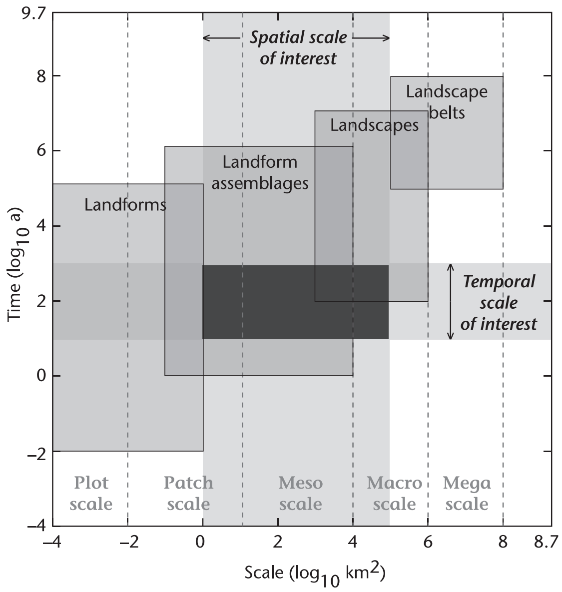

FIGURE 1.1. Spatial and temporal scales in geomorphology. On the *x*-axis, the area of the surface of the Earth in km² is expressed as 8.7 logarithmic units; on the *y*-axis, time since the origin of the Earth in years is expressed as 9.7 logarithmic units.

(b) landscape belts (*Landschaftgürtel*) and biomes, which provide an organising framework for this volume, are nevertheless so large that their response to environmental disturbance is impossible to characterise at century or shorter timescales.

The preferred range of timescales is decades–centuries (Fig. 1.1). These are intermediate temporal scales that are relevant to human life and livelihoods (and define timescales required for mitigation and adaptive strategies in response to environmental change). The determination of the future trajectory of landscape change is unthinkable for projections into a more distant future. Nevertheless, as is argued below, an understanding of changes in landscapes and biomes over the past 20 000 years (i.e. since the time of maximum continental ice sheet development over North America and Eurasia) provides essential context for a proper understanding of current and near-future landscape dynamics.

1.1.2 The global human footprint and landscape vulnerability

The human imprint on the landscape has become global (Turner *et al*., 1990a; Messerli *et al*., 2000) and positive feedbacks between climate, relief, sea level and human activity are leading in the direction of critical system state 'tipping points'. This is both the threat and the opportunity of global environmental change. Some of the implications of arriving at such a tipping point are that gradual change may be overtaken by rapid change or there may even be a reversal of previously ascertained trends. A few examples of the most vulnerable landscapes, in which small environmental changes, whether of relief, sea level, climate or land use, can produce dramatic and even catastrophic response, are listed here:

(a) Low-lying deltas in subsiding, cyclone-prone coasts are highly vulnerable to changes in tropical storm magnitude and/or frequency. It is clear that societal infrastructure is poorly attuned to disaster response in such heavily populated landscapes, in both developed (e.g. Hurricane Katrina, Mississippi Delta, August 2005) and developing (Cyclone Nargis, Irrawaddy Delta, May 2008) countries;
(b) Shifting sand dunes respond rapidly to changing temperature and rainfall patterns. Dunes migrate rapidly when vegetation is absent; the vast areas of central North America, central Europe and northern China underlain by loess (a mixture of fine sand and silt) are highly vulnerable to erosion when poorly managed, but are also an opportunity for continuing intensive agricultural activity guided by the priority of the ecosystem;
(c) Glacier extent and behaviour are highly sensitive to changing temperatures and rising sea level. In most parts of the world, glaciers are receding; in tropical regions, glaciers are disappearing altogether, with serious implications for late summer water supply; in Alaska, British Columbia, Iceland, Svalbard and the Antarctic Peninsula glaciers are surging, leading to catastrophic drainage of marginal lakes and downstream flooding. Transportation corridors and settlements downstream from surging glaciers are highly vulnerable to such dynamics;
(d) Permafrost is responding to rising temperatures in both polar and alpine regions. In polar regions, landscape impacts include collapse of terrain underlain by massive ice and a general expansion of wetlands. Human settlements, such as Salluit in northern Quebec, Canada, are highly vulnerable to such terrain instability and adaptation strategies are required now to deal with such changes; and
(e) In earthquake-prone, high-relief landscapes, the damming of streams in deeply dissected valleys by landslides has become a matter of intense concern. The 12 May 2008 disaster in Szechwan Province, China saw the creation of over 30 'quake lakes', one of which reached a depth of 750 m before being successfully drained via overspill channels. If one of these dams had

been catastrophically breached, the lives of 1.5 million downstream residents would have been endangered. Although one example does not make a global environmental concern, the quake lakes phenomenon is representative of the natural hazards associated with densely populated, tectonically active, high-relief landscapes.

1.1.3 Multiple drivers of environmental change

There is an imbalance in the contemporary debate on global environmental change in that the main emphasis is on only one driver of environmental change, namely climate (Dowlatabadi, 2002; Adger *et al*., 2005). In fact, environmental change necessarily includes climate, relief, sea level and the effects of land management/anthropogenic factors *and* the interactions between them. It is important that a rebalancing takes place now, to incorporate all these drivers. Furthermore, the focus needs to be directed towards the landscape scale, such that global environmental changes can be assessed more realistically. Human safety and wellbeing and the maintenance of Earth's geodiversity will depend on improved understanding of the reciprocal relations between landscapes and the drivers of change.

In his book *Catastrophe*, for example, Diamond (2005) has described a number of ways in which cultures and civilisations have disappeared because, at least in part, those civilisations have not understood their vulnerability to one or more of the drivers of environmental change. Montgomery (2007) has developed a similar thesis with a stronger focus on the mismanagement of soils.

1.1.4 Systemic and cumulative global environmental change

Global environmental change is here defined as environmental change that consists of two components, namely systemic and cumulative change (Turner *et al*., 1990b). Systemic change refers to occurrences of global scale, physically interconnected phenomena, whereas cumulative change refers to unconnected, local- to intermediate-scale processes which have a significant net effect on the global system.

In this volume, hydroclimate and sea level change are viewed as drivers of systemic change (see Sections 1.6 and 1.7 of this chapter below). The atmosphere and ocean systems are interconnected across the face of the globe and the modelling of the coupled atmosphere–ocean system (AOGCM) has become a standard procedure in application of general circulation models (or GCMs). A GCM is a mathematical representation of the processes that govern global climate. At its core is the solution to a set of physical equations that govern the transfer of mass, energy and momentum in three spatial dimensions through time. The horizontal atmospheric resolution of most global models is between 1°–3° (~100–300 km). Processes operating at spatial scales finer than this grid (such as cloud microphysics and convection) are parameterised in the model. In the vertical direction, global models typically divide the atmosphere into between 20 and 40 layers.

Topographic relief, and land cover and land use changes, by contrast, are viewed as drivers of cumulative change (see Sections 1.8 and 1.9). The patchiness of relief and land use and difficulties of both definition and spatial resolution make the incorporation of their effects into GCMs a continuing challenge. Nevertheless, developments in global climate modelling over the past decade have seen the improvement in land-surface modelling schemes in which an explicit representation of soil moisture, runoff and river flow routing has been incorporated into the modelling framework (Milly *et al*., 2002). This trend, coupled with the widespread implementation of dynamic vegetation models (in which vegetation of different plant functional types is allowed to grow according to prevailing environmental conditions) has resulted in a generation of models into which such a range of complex interacting processes are embedded that they have become termed global *environmental* models instead (Johns *et al*., 2006).

1.1.5 The role of geomorphology

In these contexts, geomorphology (from the Greek *geo* Earth and *morphos* form) has an important role to play; it involves the description, classification and analysis of the Earth's landforms and landscapes and the forces that have shaped them, over a wide range of time and space scales (Fairbridge, 1968). In particular, geomorphology has the obligation to inform society as to what level of disturbance the Earth's landforms and landscapes can absorb and over what time periods the landscape will respond to and recover from disturbance.

In this book, we have chosen to view geomorphology (changing landforms, landform systems, landscapes and landscape systems) as dependent on the four drivers of environmental change, namely climate, relief, sea level and human activity, but also as an independent variable that has a strong effect on each of the drivers at different time and space scales. The relationship in effect is a reflexive one and it is important to avoid the implication of unique deterministic relations.

Two important intellectual strands in geomorphology have been so-called 'climatic' and 'process' geomorphology; they have tended to focus on different spatio-temporal scales of inquiry.

1.2 Climatic geomorphology

Climate's role in landscape change has long been of interest to geomorphology. Indeed in the continental European literature this was a theme that was already well developed by the end of the nineteenth century (Beckinsale and Chorley, 1991). The greatest impetus to climatic geomorphology came from the global climatic classification scheme of Köppen (1901). A clear statement of the concept of climatic geomorphology was made by de Martonne (1913) in which he expressed the belief that significantly different landscapes could be developed under at least six present climatic regimes and drew particular attention to the fact that humidity and aridity were, in general, more important as differentiators of landscape than temperature. The identification of morphoclimatic/morphogenetic regions and attempts to identify global erosion patterns (Büdel in Germany, Tricart in France and Strakhov in Russia) were also important global-scale contributions. Strakhov's map of global-scale erosion patterns is reproduced here (Fig. 1.2) to illustrate the style and scale of this research. He attempted to estimate world denudation rates by extrapolating from sediment yields for 60 river basins. His main conclusions were:

(a) arid regions of the world have distinctive landforms and landscapes;
(b) the humid areas of the tropics and subtropics, which lie between the +10 °C mean annual isotherm of each hemisphere, are characterised by high rates of denudation, reaching maximum values in southeastern Asia;
(c) the temperate moist belt, lying largely north of the +10 °C mean annual isotherm, experiences modest denudation rates;
(d) the glaciated shield areas of the northern hemisphere, largely dominated by tundra and taiga on permafrost and lying north of the 0 °C mean annual isotherm, have the lowest recorded rates of denudation; and
(e) mountain regions, which experience the highest rates of denudation, are sufficiently variable that he was forced to plot mountain denudation data separately in graphical form.

The map is an example of climatic geomorphology in so far as it demonstrates broad climatic controls but perhaps the most important contribution of twentieth-century climatic geomorphology was that it maintained a firm focus on the landscape scale, the scale to which this volume is primarily directed. The weakness of the approach is that regional and zonal generalisations were made primarily on the basis of form (in the case of arid regions) and an inadequate sampling of river basin data. There was a lack of field measurements

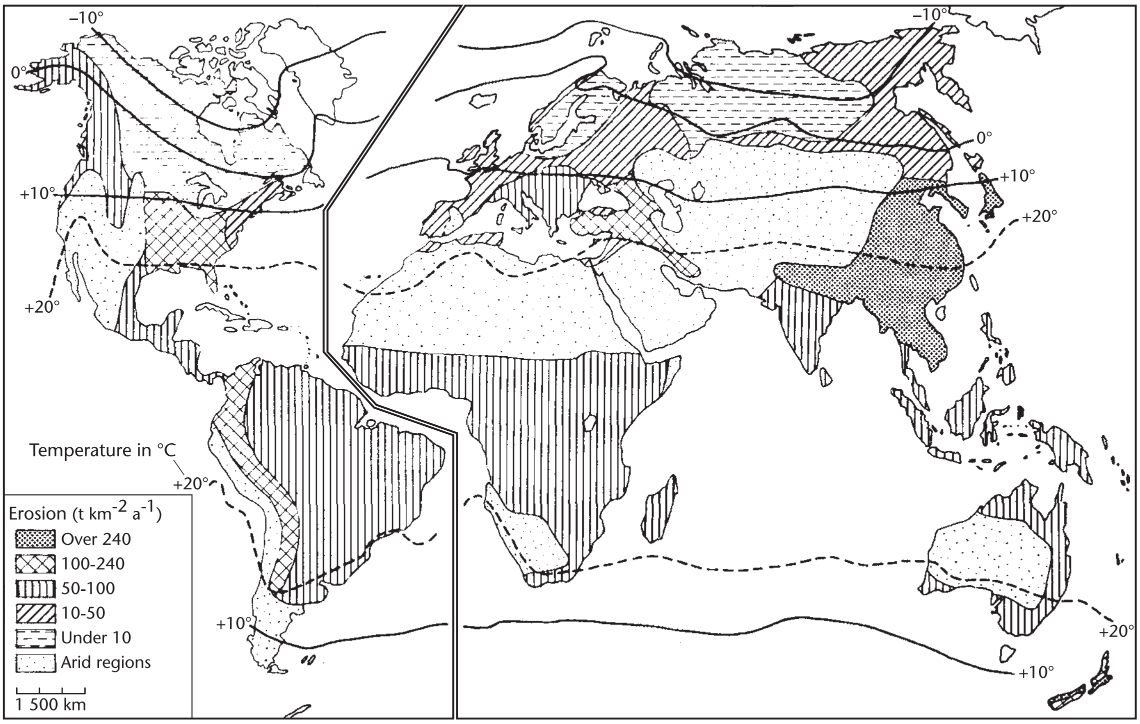

FIGURE 1.2. Climatic geomorphology (modified from Strakhov, 1967).

of contemporary process and no discussion of the scale dependency of key rainfall, runoff and sediment relations.

Whilst one may be critical of these earlier attempts to deal with landscape-scale geomorphology, now is a good time to revisit the landscape scale, with a firmer grasp of the relief, sea level and human activity drivers, for the following reasons:

(a) the development of plate tectonic theory and its geomorphological ramifications has given the study of earth surface processes and landforms a firmer geological and topographic context;
(b) a better understanding of the magnitudes and rates of geomorphological processes has been achieved not only from contemporary process measurements but also from the determination of more precise and detailed records of global environmental change over the last 20 000 years utilising improved chronologies (largely ocean rather than terrestrially based) and benefiting from the development of whole suites of radiometric dating techniques, covering a wide range of half-lives and thus timescales; and
(c) the ability to provide, at a range of scales, quantitative measurements of land surface topography and vegetation characteristics from satellite and airborne remote sensing.

1.3 Process geomorphology

From the 1950s onwards an Anglo-American geomorphology came to be reorientated towards quantitative research on the functional relations between form, materials and earth surface processes. These 'process studies', generally at the scale of the small drainage basin or below, began to determine local and regional rates of surface lowering, or denudation, material transport and deposition and their spatial differentiation. The rates at which these processes take place are dependent upon local relief and topography, the materials (bedrock and soils) involved and, of course, climate, both directly and indirectly through the relations between climate, vegetation characteristics and surface processes. The emphasis on rates of operation of processes led to a greater interest in the role of hydroclimate, runoff and sediment transport both in fluvial and in coastal systems. The role of vegetation in landscape change also assumed a new importance for its role in protecting the soil surface, in moderating the soil moisture and climate and in transforming weathered bedrock into soil (Kennedy, 1991).

1.3.1 Process–response systems

One of the most influential papers in modern geomorphology concerned the introduction of general systems thinking

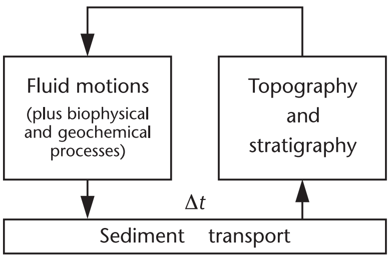

FIGURE 1.3. A simplified conceptual model of a process–response system.

into geomorphology (Chorley, 1962). General systems thinking provided the tool for geomorphologists to analyse the critical impacts of changes in the environmental system on the land surface, impacts of great importance for human society and security. One kind of general system that has proved to be most fruitful in providing explanations of the land surface–environment interaction is the so-called process–response system (Fig. 1.3). Such systems are defined as comparatively small-scale geomorphic systems in which deterministic relations between 'process' (mass and energy flows) and 'response' (changes in elements of landscape form) are analysed with mathematical precision and attempted accuracy. There is a mutual co-adjustment of form and process which is mediated through sediment transport, a set of relations which has been termed 'morphodynamics' and which has been found to be particularly useful in coastal studies (e.g. Woodroffe, 2002).

Morphodynamics explains why, on the one hand, physically based models perform well at small spatial scales and over a limited number of time steps but, on the other hand, why model predictions often break down at 'event' and particularly 'engineering' space-timescales. Unfortunately, these are exactly the scales that are of greatest significance in the context of predicting landscape responses to global environmental change and the policy and management decisions that flow from such responses.

1.3.2 The scale linkage problem

The issue of transferring knowledge between systems of different magnitude is one of the most intransigent problems in geomorphology, both in terms of temporal scale and spatial scale (Church, 1996).The problem of scale linkage can be summarised by the observation that landscapes are characterised by different properties at different scales of investigation. Each level of the hierarchy includes the cumulative effects of lower levels in addition to some new considerations (called emergent properties in the technical literature) (Fig. 1.4).

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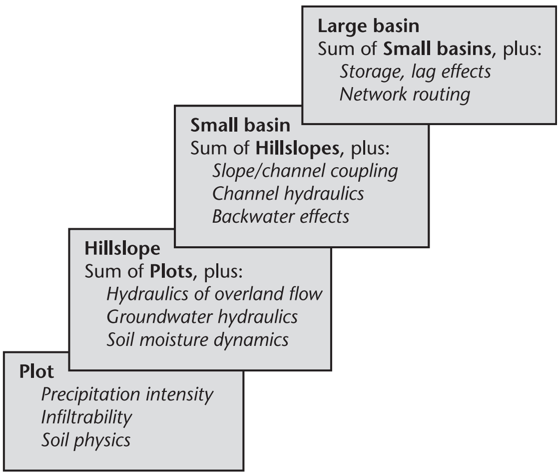

FIGURE 1.4. The scale linkage problem (modified from Phillips, 1999) illustrated in terms of a spatial hierarchy which contains new and emergent properties at each successive spatial scale.

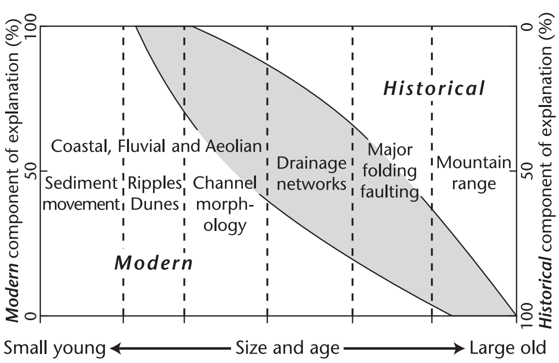

FIGURE 1.5. The relative importance of historical vs. modern explanation as a function of size and age of landforms and landscapes (modified from Schumm, 1985). Note the assumption that size and age are directly correlated, an assumption that is most appropriate for coastal, fluvial and aeolian landscapes, but does not easily fit volcanic and tectonic landscapes.

At the landscape scale, here taken to be larger than the large basin scale in Fig. 1.4, there are further emergent properties which have to be considered such as regional land use and hydrology.

Figure 1.5 combines a consideration of both temporal and spatial scales. At one extreme of very small spatial scale, such as the movement of individual sand grains over very short timescales, the process–response model works well. At the other extreme, large landscapes that have evolved over millions of years owe their configuration almost exclusively to past processes. Discontinuous sediment disturbances have a history of variable magnitude and frequency of occurrence. The practical implication is that, in general, the larger the landscape we wish to consider the more we have to take into account past processes and the slower will be the response of that landscape in its entirety to sediment disturbance regimes. Coastal morphology and drainage networks, which occupy the central part of Fig. 1.5, exemplify the scales of interest in this volume.

1.4 Identification of disturbance regimes

Global environmental change has become a major concern in geomorphology because it poses questions about the magnitude, frequency and kinds of disturbance to which geomorphic systems are exposed. What then are the major drivers of that change? Discussions about the rhythm and periodicity of geological change have spilled over into geomorphology. In his discussion of rhythmicity in terrestrial landforms and deposits, Starkel (1985) directed attention to the fact that the largest disturbance in the geologically recent past is that of continental-scale glaciation (see Plates 1 and 2). Periods of glaciation alternating with warmer episodes define a disturbance regime characterised by varying rates of soil formation and erosional and depositional geomorphological processes during interglacial and glacial stades (Fig. 1.6).

Some of the excitement in the current debate over global environmental change concerns precisely the question of the rate at which whole landscapes have responded to past climate changes and disturbances introduced by tectonism (e.g. volcanism, earthquakes and tsunamis) or human activity.

1.4.1 Landscape response to disturbance

The periodicity of landscape response to disturbance in Fig. 1.6 is controlled by the alternation of glacial and interglacial stades. The magnitude and duration of this response is a measure of the sensitivity and resilience of the landscape. In the ecological and geomorphic literature, this response is commonly called the system vulnerability. Conventionally, human activity has been analysed outside

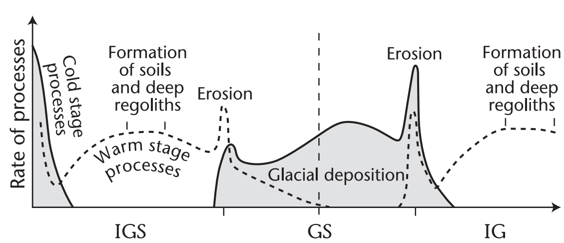

FIGURE 1.6. Periodicity of erosion and sedimentation (modified from Starkel, 1985). IGS is interglacial stade; GS is glacial stade; and IG is the present interglacial.

the geosystem (and Fig. 1.6 contains no human imprint) but the weakness of this approach is that it fails to recognise the accelerating interdependence of humankind and the geosystem. The IPCC usage of the term 'vulnerability', by contrast, addresses the ability of society to adjust to disturbances caused by environmental change. We therefore follow, broadly, the IPCC approach in defining sensitivity, adaptive capacity and vulnerability as follows. 'Sensitivity' is the degree to which a system is affected, either adversely or beneficially, by environment-related stimuli; 'adaptive capacity' is the ability of a system to adjust to environmental change, to moderate potential damages, to take advantage of new opportunities or to cope with the consequences; and 'vulnerability' is the degree to which a system is susceptible to, or unable to cope with, adverse effects of environmental change. In sum, 'vulnerability' is a function of the character, magnitude and rate of environmental change and variation to which a system is exposed, its sensitivity and its adaptive capacity (Box SPM-1 in IPCC, 2001b, p. 6.).

In general, those systems that have the least capacity to adapt are the most vulnerable. Geomorphology delivers a serious and often unrecognised constraint to the feasible ways of dealing with the environment in so far as it controls vulnerability both in the ecological sense (in the absence of direct human agency) *and* in the IPCC sense. A number of unique landscapes and elements of landscapes are thought to be more likely to experience harm than others following a perturbation. There are seven criteria that have been used to identify key vulnerabilities:

(a) magnitude of impacts;
(b) timing of impacts;
(c) persistence and reversibility of impacts;
(d) estimates of uncertainty of impacts;
(e) potential for adaptation;
(f) distributional aspects of impacts; and
(g) importance of the system at risk.

In the present context, such landscapes are recognised as hotspots with respect to their vulnerability to changes in climate, relief, sea level and human activities. We think immediately for example of glaciers, permafrost, coral reefs and atolls, boreal and tropical forests, wetlands, desert margins and agricultural lands as being highly vulnerable. Some landscapes will be especially sensitive because they are located in zones where it is forecast that climate will change to an above average degree. This is the case for instance in the high arctic where the degree of warming may be three to four times greater than the global mean. It may also be the case with respect to some critical areas where particularly substantial changes in precipitation may occur. For example, the High Plains of the USA may become markedly drier. Other landscapes will be especially sensitive because certain landscape forming processes are particularly closely controlled by thresholds, whether climatic, hydrologic, relief, sea level or land use related. In such cases, modest amounts of environmental change can switch systems from one state to another (Goudie, 1996).

1.4.2 Azonal and zonal landscape change

The overarching problem of assessing probable landscape change in the twenty-first century is approached here in two main ways. A group of chapters which are 'azonal' in character concern themselves with ways in which geomorphic processes are influenced by variations in mass, energy and information flows, and this self-evidently includes human activity. These azonal chapters deal with land systems that are larger than individual slopes, stream reaches and pocket beaches, but generally smaller than continental-scale regions. By comparison, the zonal chapters use whole biomes as their organising principle, similar to those used in the Millennium Ecosystem Assessment (2003) (Plate 3). In these chapters also, environmental change is driven, not only by hydroclimate, relief and sea level but also by human activity.

In addition to understanding the terrestrial distribution of biomes, it is also important to recognise the broad limits to coral reef and associated shallow water ecosystems, such that the upper ocean's vulnerability to global environmental change can also be assessed (Fig. 1.7).

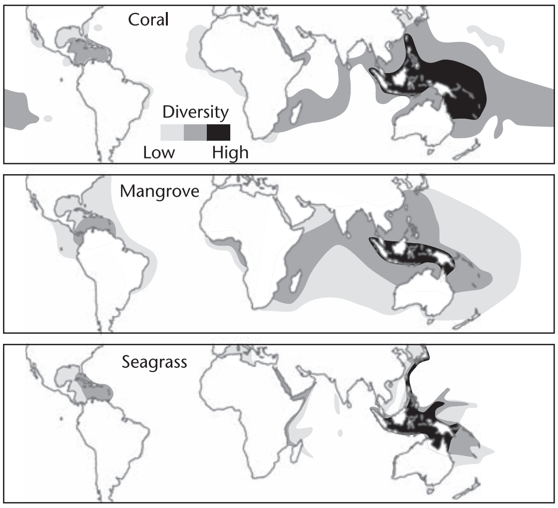

FIGURE 1.7. Global distribution of coral reefs, mangroves and seagrass. Scale of diversity ranges from 0–10 genera (low); 10–25 genera (medium); and >50 (high) (modified from Veron, 1995).

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The decision to structure the book chapters using a bottom–up (azonal) and a top–down (zonal) approach reflects the fact that both approaches have complementary strengths.

1.5 Landscape change

Geomorphology emphasises landscape change under the influence of climate, relief, sea level change and human activity (Chorley *et al.*, 1984) and does so at a range of space and timescales. With respect to temporal scales, attention is confined in this volume to the last complete glacial–interglacial cycle and forward towards the end of the twenty-first century (Fig. 1.8). The reasons for the selection of these end points are that they include one complete glacial–interglacial cycle (see Chapter 14), and thus the widest range of climates and sea levels in recent Earth history. This period includes the rise of *Homo sapiens sapiens*; and extends forward to a time when future landscapes can be modelled with some confidence and for which credible scenarios of landscape change can be constructed.

Included in this timescale are the closing stages of the Pleistocene Epoch (150 000 to 10 000 years ago); the Holocene Epoch (10 000 years BP until the present) and a recent, more informally defined, Anthropocene, extending from about 300 years ago when human impact on the landscape became more evident, and into the near future. The comprehensive ice core records from Greenland (GISP and GRIP) and from Antarctica (Vostok and EPICA) (Petit *et al.*, 1999; EPICA, 2004) (Fig. 1.8); lake sediments from southern Germany (Ammersee) (Burroughs, 2005) (Fig. 1.9) and elsewhere; and a number of major reconstructions of the climate of the last 20 000 years using past scenarios (Plates 1 and 2) provide a well-authenticated record of the Earth's recent climatic history.

The record of changing ice cover and biomes since the Last Glacial Maximum (LGM) has been reconstructed by an international team of scientists working under the general direction of the Commission for the Geological Map of the World (Petit-Maire and Bouysse, 1999; Plates 1 and 2). The authors stress that the maps are tentative but contain the best information that was available in 1999. The maps depict the state of the globe during the two most

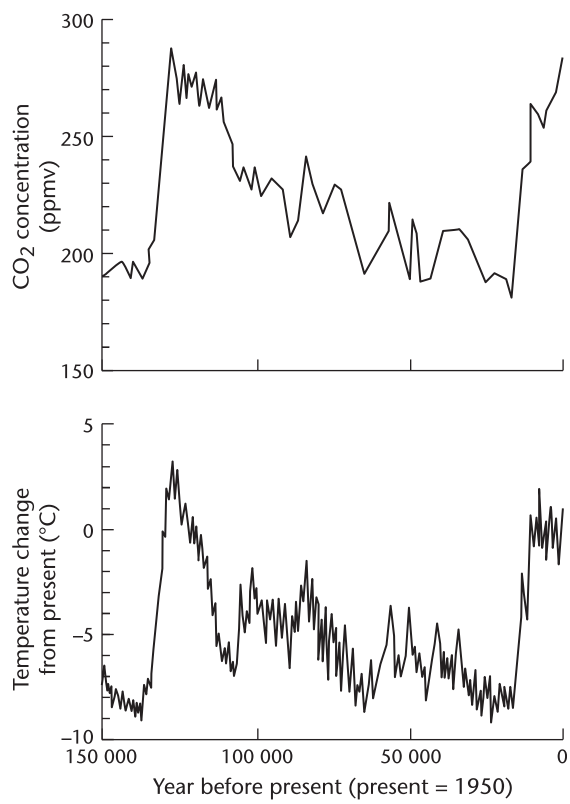

FIGURE 1.8. Climate records from East Antarctica (Vostok ice core) covering the last glacial–interglacial cycle (modified from Petit *et al.*, 1999). Note the rapid warming followed by a gentler, stepped cooling process and also the close correlation of temperature and CO_2.

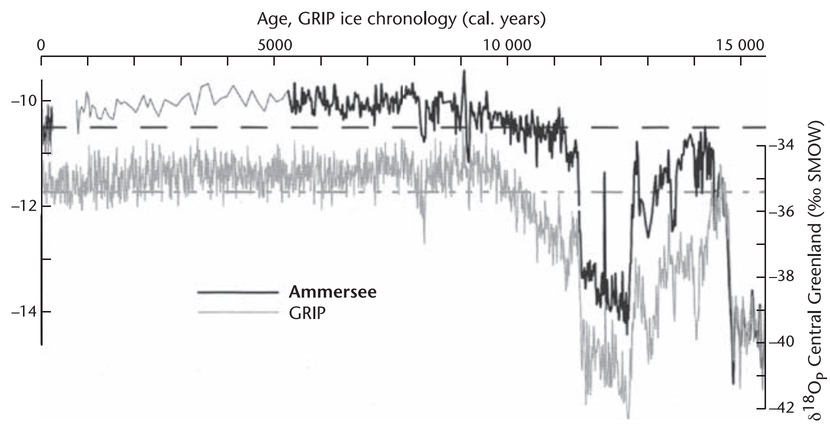

FIGURE 1.9. A comparison of the record from Ammersee, in southern Germany, and the GRIP ice core from Greenland showing the close correlation between the Younger Dryas cold event from 12.9 to 11.6 ka BP at the two sites (from von Grafenstein *et al.*, 1999).

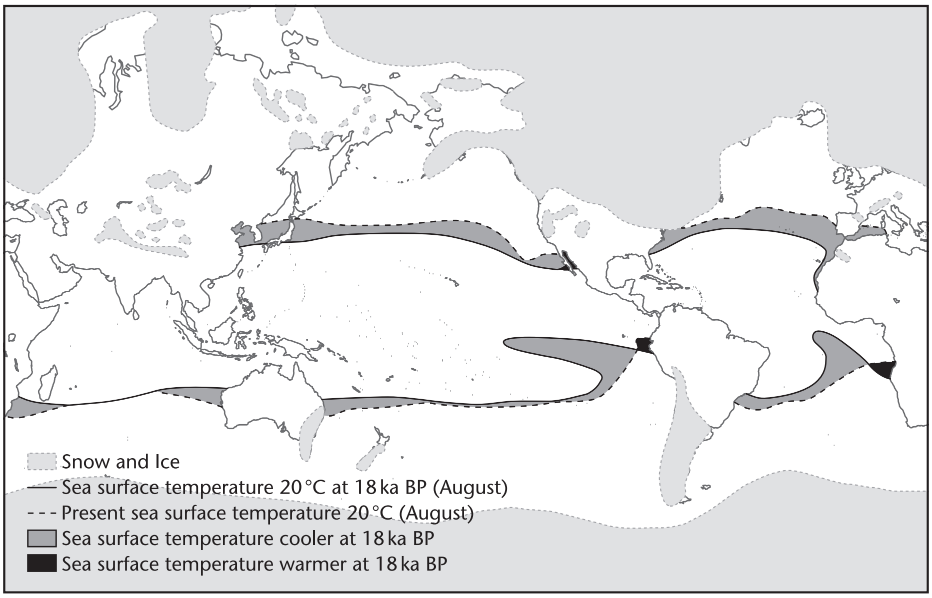

FIGURE 1.10. Changing tropical ocean temperatures, LGM to present (modified from CLIMAP, 1976 and Spencer, 1990).

contrasted periods of the last 20 ka. The LGM was the coldest (*c*. 18 ka ± 2 ka BP) and the Holocene Optimum (HOP) was the warmest (*c*. 8 ka ± 1 ka BP) period. These periods were only 10 ka apart and yet there was a dramatic reorganisation of the shorelines, ice cover, permafrost, arid zones, surface hydrology and vegetation at the Earth's surface over that interval. Thus within a 10-ka time-span (in many places less) the two vast ice sheets of Canada and Eurasia, which reached a height of 4 km and covered about 25 million km², disappeared; 20 million km² of continental platform were submerged by the sea; biomes of continental scale were transformed and replaced by new ones; and humans could no longer walk from Asia to America nor from New Guinea to Australia nor from France to England.

It is also interesting to compare these shifts in the terrestrial landscape with change in sea surface temperatures over the same period of time. In particular, in the tropical oceans, these changes were relatively small – as illustrated by the change in the 20 ºC isotherm (which provides a broad limit to coral growth) – with the greatest changes being in the variable strength of the equatorial upwelling systems on the eastern margins of the ocean basins (Fig. 1.10).

1.5.1 The Last Glacial Maximum

First of all, there needs to be a caveat with respect to the timing of the LGM (Plate 1). There is strong evidence that the maximum extent of ice was reached in different places at different times. The ice distribution that is mapped corresponds to the maximum extent during the time interval 22 ka to 14 ka years BP, which covers the global range within which the maximum is believed to have occurred. During the LGM, mean global temperature was at least 4.5 °C colder than present. Permafrost extended southwards to latitudes of 40–44º N in the northern hemisphere (although in the south, only Patagonia and the South Island of New Zealand experienced permafrost). Mean sea level was approximately 125 m lower than at present. Large areas of continental shelf were above sea level and colonised by terrestrial vegetation, particularly off eastern Siberia and Alaska, Argentina, and eastern and southern Asia. New Guinea was connected to Australia, the Persian Gulf dried up and the Black Sea, cut off from the Mediterranean Sea, became a lake.

There was a general decrease in rainfall near the tropics. Loess was widespread in periglacial areas and dunes in semi-arid and arid regions. All desert areas were larger than today but in the Sahara there was the greatest southward extension of about 300–400 km. Surface hydrology reflected this global aridity except in areas that received meltwaters from major ice caps, such as the Caspian and Aral seas. Grasslands, steppes and savannas expanded at the expense of forests.

1.5.2 The record from the ice caps and lake sediments

The transition between the LGM and the Holocene was marked by a partial collapse of the Laurentide/Eurasian ice sheets. This led to a surge of icebergs, recorded in the sediments of the North Atlantic by the last of the so-called Heinrich events (thick accumulations of ice-rafted sediments) around 16.5 ka. There followed a profound warming around 14.5 ka (Fig. 1.9) which coincided with a rapid rise in sea level (see Section 1.7), presumably associated with the break-up of part of the Antarctic ice sheet (Burroughs, 2005).

Between 14.5 and 12 ka BP the mean annual temperature oscillated violently and between 12.9 and 11.6 ka the last great cooling of the ice age (known as the Younger Dryas stade) occurred. Rapid warming continued until around 10 ka but thereafter, the climate seems to have settled into what looks like an extraordinarily quiet phase when compared with the earlier upheavals. The Holocene Epoch is conventionally said to start around 10 ka because the bulk of the ice sheet melt had occurred by that time, but the Laurentide ice sheet, for example, did not disappear until 6 ka BP.

Although climatic fluctuations during the Holocene have been much more modest than those which occurred during the previous 10 ka, there have been fluctuations which have affected glacier distribution in the mountains, treeline limits in the mountains and in the polar regions, and desiccation of the Sahara. The CASTINE project (Climatic Assessment of Transient Instabilities in the Natural Environment) has identified at least four periods of rapid climate change during the Holocene, namely 9–8 ka; 6–5 ka; 3.5–2.5 ka and since 0.6 ka. In terms of landscape history, it is also important to recognise that the mean global temperature may not be the most significant factor in landscape change. Precipitation amounts and soil moisture availability and their variability of occurrence and intensity over space and through time have had a strong influence on regional and local landscape evolution.

1.5.3 The Holocene Optimum

A caveat also needs to be applied with respect to the timing of the HOP (Plate 2). The maximum values of the signals for each of the various indicators of environmental change are far from being coeval. During the HOP, the mean global temperature was about 2 °C warmer than today. By 6 ka BP, mean relative land and sea level was close to that of the present day except in two kinds of environments:

(a) the Canadian Arctic and the Baltic Sea where isostatic (land level rebound after ice sheet load removal) adjustments were at a maximum;
(b) deltas of large rivers, such as the Mississippi, Amazon, Euphrates–Tigris and Yangtze, had not reached their present extent.

The glacier and ice sheet cover cannot be distinguished from that of today at this global scale. Permafrost, both continuous and discontinuous, was within the present boundary of continuous permafrost in the northern hemisphere. Significantly wetter conditions were experienced in the Sahara, the Arabian Peninsula, Rajasthan, Natal, China and Australia, where many lakes that have subsequently disappeared were formed. In Canada the Great Lakes were formed following the melting of the ice sheet and the isostatic readjustment of the land. Rainforest had recolonised extensive areas and the taiga and boreal forest had replaced a large part of the tundra and areas previously covered by ice sheets (Petit-Maire, 1999).

This time-span of 20 000 years has been selected in order to encapsulate the extremes of mean global cold and warmth experienced between the LGM and the HOP, a range that one might expect to contain most of the reasonable scenarios of environmental change over the next 100 years. Certainly, this range defines the 'natural' variability of Earth's landscapes but, notably, little distinctive human impact was discernible at this global scale of analysis.

Recently, however, Ruddiman (2005) has claimed to recognise the effects of human activity in reversing the trends of CO_2 and methane concentrations around 8–5 ka BP. His hypothesis is that clearing of the land for agriculture and intensification of land use during the Holocene has so altered the climate as to delay the arrival of the next glacial episode. This is a controversial hypothesis which requires further testing. If the hypothesis is supported, it emphasises the importance of the warning issued by Steffen *et al.* (2004) against the use of Pleistocene and Holocene analogues to interpret the Anthropocene, the contemporary epoch which is increasingly dominated by human activity and is therefore a 'no analogue' situation.

1.6 Systemic drivers of global environmental change (I): hydroclimate and runoff

1.6.1 Introduction

Water plays a key role in the transfer of mass and energy within the Earth system. Incoming solar radiation drives the evaporation of approximately 425×10^3 km^3 a^{-1} of water from the ocean surface and approximately 71×10^3 km^3 a^{-1} from the land surface; precipitation delivers about 385×10^3 km^3 a^{-1} of water to the ocean and 111×10^3 km^3 a^{-1} to the land surface. The balance is redressed through the flow of 40×10^3 km^3 a^{-1} of water from the land to the oceans in rivers (Berner and Berner, 1996). Global environmental change affecting any one of these water transfers will lead