Part II

The Future

8 THE FUTURE: INTRODUCTION

Introduction

According to a range of modeling studies, it is highly likely that human induced global warming, produced by the emissions of a cocktail of greenhouse gases into the atmosphere, is now occurring and will continue to affect the global climate for decades and centuries. Concentrations of carbon dioxide, methane, nitrous oxide, and the chlorofluorocarbons, all greenhouse gases, have increased. The international body charged with such matters, The Intergovernmental Panel on Climate Change (IPCC), set up in the 1980s, has considered these changes in some detail (e.g., IPCC, 2001).

The atmospheric concentration of CO_2 has increased by 31% since 1750 and the present CO_2 concentration has not been exceeded during the past 420,000 years and possibly during the past 20 million years (IPCC, 2001: 7). The atmospheric concentration of methane has increased by over 150% since 1750 and that of nitrous oxide by 17%. Chlorofluorocarbons (CFCs), which are entirely artificial, have been emitted, and although the Montreal Protocol and its amendments may control them, they have a long residence time in the atmosphere.

During the twentieth century the global average surface temperature increased by around 0.6°C (IPCC, 2001: 2). The 1990s were the warmest decade in the instrumental record and in the Northern Hemisphere the increase in temperature is likely to have been the largest of any century during the past 1000 years.

The IPCC (2001: 13) suggests that global average surface temperatures will rise by 1.4 to 5.8°C between 1990 and 2100. This represents a much larger rate of warming than that observed over the twentieth century and, based on paleoclimatic data, is very likely to surpass anything experienced over the past 10,000 years. In its turn, increased temperatures will transform the behavior of the atmospheric heat engine that drives the general circulation of the air and the oceans, leading to changes in the nature, pattern, and amount of precipitation. Table 8.1, adapted from the IPCC (2001, table 1), indicates some of the projections for future climate. In particular it is likely that northern high latitudes will warm more rapidly than the global average, probably by more than 40%. There may also be marked changes in precipitation, with a tendency for increases to occur globally, but particularly over

Table 8.1 Key projections of climate trends and extreme events in the IPCC Third Assessment. Source: adapted from Houghton et al. (2001)

Change	*Likelihood**
Rate of increase of global surface temperature will exceed anything experienced over past 10,000 years	Very likely
Nearly all land areas will warm more than global average, particularly northern high latitudes in cold season	Very likely
Precipitation will increase by end of twenty-first century over northern mid- to high latitudes in winter	Likely
In areas where increase in mean precipitation is predicted, larger year-to-year variations will occur	Very likely
Higher maximum temperature and more hot days over nearly all land areas	Very likely
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Reduced diurnal temperature range over most land areas	Very likely
More intense precipitation events over many Northern Hemisphere mid- to high latitude land areas	Very likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities	Likely, over some areas

*Very likely = 90–99% chance; likely = 66–90%.

northern mid- to high latitudes and Antarctica in winter. At lower latitudes some areas will see reductions in precipitation (which will exacerbate soil moisture losses caused by increased evapotranspiration), while others may become wetter.

If global warming and associated changes in rainfall and soil moisture amounts occur, then the effects on natural environments may be substantial and rapid. These impacts have been reviewed by the IPCC (Watson et al., 1996). The following are some of the thought-provoking comments made in their report.

On forests: 'A substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types . . . climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce and establish themselves . . . the species composition of forests is likely to change; entire forest types may disappear.'
On deserts and desertification: 'Deserts are likely to become more extreme – in that, with few exceptions, they are projected to become hotter but not significantly wetter.'
On the cryosphere: 'Between one-third and one-half of existing mountain glacier mass could disappear over the next 100 years.'
On mountain regions: 'The projected decrease in the extent of mountain glaciers, permafrost and snow cover caused by a warmer climate will affect hydrologic systems, soil stability and related socio-economic systems . . . Recreational industries – of increasing economic importance to many regions – are also likely to be disrupted.'
On coastal systems: 'Climate change and a rise in sea level or changes in storm surges could result in the erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, a change in the pattern of chemical and microbiological contamination in coastal areas, and increased coastal flooding. Some coastal ecosystems are particularly at risk, including saltwater marshes, mangrove ecosystems, coastal wetlands, coral reefs, coral atolls, and river deltas.'

Some landscape types will be highly sensitive to global warming. This may be the case because they are located in zones where it is forecast that climate will change to an above average degree. This applies, for instance, in the high latitudes of North America and Eurasia, where the degree of warming may be three or four times greater than the presumed global average. It may also be the case for some critical areas where particularly substantial changes in rainfall may result from global warming. For example, various methods of climatic prediction produce scenarios in which the American High Plains will become considerably drier. Other landscapes will be highly sensitive because certain landscape-forming processes are very closely controlled by climatic conditions. If such landscapes are close to a particular climatic threshold then quite modest amounts of climate change can switch them from one state to another.

There are, of course, considerable uncertainties built into any consideration of the future. Our models are crude and relatively simple and it is difficult to build in all the complexities and feedbacks in the atmosphere, pedosphere, lithosphere, oceans, biosphere, and cryosphere. Different models often provide very different future scenarios, particularly with respect to future rainfall amounts. Other difficulties are presented by the existence of nonlinearities and thresholds in natural systems. There may be complex responses to change and sometimes indeterminable time lags. There are also great uncertainties about how emissions of greenhouse gases will change in coming decades as a result of changes in the global economy, technological changes, and the adoption of mitigation strategies.

Furthermore, many of our models have a coarse spatial resolution and are difficult to use at more local scales. It is also problematic to use past warm phases as analogues for the future, for the driving mechanisms may be different. Finally, changes brought about by enhanced greenhouse loadings cannot be seen in isolation. They will occur concurrently with other natural and anthropogenic climatic changes. In some cases other human activities could compound (or reverse) the effects of global warming.

The causes, consequences, and controversies associated with global warming have been treated extensively elsewhere (e.g., Harvey, 2000). The purpose of the following chapters of this book is not to review and revisit this literature, but to examine the implications that global warming has for landscapes and habitats.

Changes in the biosphere

Climate change and changes in the concentrations of carbon dioxide in the atmosphere are likely to have a whole suite of biological consequences (Gates, 1993; Joyce et al., 2001). The ranges and the productivity of organisms will change.

Altitudinal changes in vegetation zones will be of considerable significance. In general, Peters (1988) believes that with a 3°C temperature change vegetation belts will move about 500 m in altitude. One consequence of this would be the probable elimination of Douglas fir (*Pseudotsuga taxifolia*) from the lowlands of California and Oregon, because rising temperatures would preclude the seasonal chilling this species requires for seed germination and shoot growth. In the twentieth century there is some evidence that warming did indeed affect the position of the tree line, and Kullman (2001), for example, found that in Sweden a 0.8°C warming in the past 100 years caused the tree limit to migrate upwards by more than 100 m.

Vegetation will also change latitudinally and some models suggest that wholesale change will occur in the distribution of biomes. Theoretically a rise of 1°C in mean temperature could cause a poleward shift of vegetation zones of about 200 km (Ozenda and Borel, 1990). However, uncertainties surround the question of how fast plant species would be able to move to and to settle new habitats suitable to the changed climatic conditions. Post-glacial vegetation migration rates appear to have been in the range of a few tens of kilometers per century. For a warming of 2–3°C forest bioclimates could shift northwards about 4–6° of latitude in a century, indicating the need for a migration rate of some tens of kilometers per decade. Furthermore, migration could be hampered because of natural barriers, ecological fragmentation, zones of cultivation, etc.

Changes in forest composition or location could be slow, for mature trees tend to be long-lived and resilient. This means that they can survive long periods of marginal climate. However, it is during the stage of tree regeneration or seedling establishment that they are most vulnerable to climate change. Seedlings are highly sensitive to temperature and may not be able to grow under altered climatic conditions. This means that if climate zones do indeed shift at a faster rate than trees migrate, established adults of appropriate species and genotypes will be separated from the place where seedling establishment is needed in the future (Snover, 1997). It is probable that future climate change will not cause catastrophic dieback of forests, but that faster growing tree species will enter existing forests over extended time periods (Hanson and Weltzin, 2000).

An early attempt to model changes on a global basis was made by Emmanuel et al. (1985). Using the global climate model (GCM) developed by Manabe and Stouffer (1980) for a doubling of CO_2 levels, and mapping the present distribution of ecosystem types in relation to contemporary temperature conditions, they found *inter alia* that the following changes would take place: boreal forests would contract from their present position of comprising 23% of total world forest cover to less than 15%; grasslands would increase from 17.7% of all world vegetation types to 28.9%;

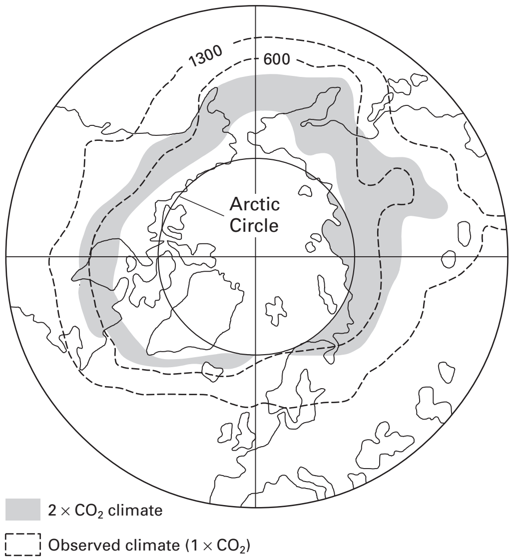

Figure 8.1 The northern and southern boundaries of the boreal forest are approximately defined by the 600 and 1300 growing degree-day isopleths. These are shown in their current positions and in the positions they would occupy under a warming associated with a doubling of CO_2 levels (after Kauppi and Posch, 1988).

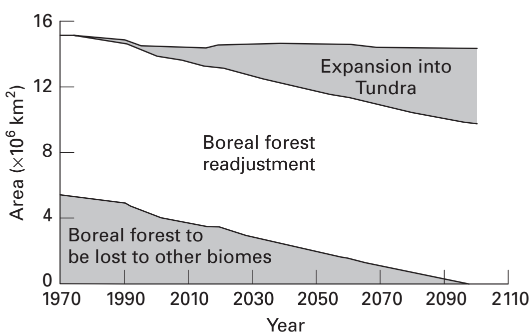

Figure 8.2 Changes in areas of boreal forest projected by the Integrated Model to Assess the Global Environment (IMAGE) in response to scenarios of future change in climate and land use. Although the total area of boreal forest is projected to remain relatively constant, about one-third of the present boreal forest is projected to be converted to other biomes, and an additional third will be added as trees advance into tundra. (Source: Chapin and Danell, 2001, figure 6.1.)

deserts would increase from 20.6 to 23.8%; and forests would decline from 58.4 to 47.4%. Potential changes in the geographical extent of boreal forests in the Northern Hemisphere are especially striking. Kauppi and Posch (1988), using a Goddard Institute for Space Studies (GISS) GCM, modeled the northern and southern boundaries of the boreal forest in response to a climate warming associated with a doubling of atmospheric carbon dioxide levels (Figure 8.1). Note how the southern boundary moves from the southern tip of Scandinavia to the northernmost portion.

Table 8.2 Changes in areal coverage ($km^2 \times 10^3$) of major biomes as a result of climatic conditions predicted for a $2 \times CO_2$ by various general circulation models (GCMs). Source: from Smith et al. (1992, table 3)

Biome	*Current*	*OSU*	*GFDL*	*GISS*	*UKMO*
Tundra	939	–302	–5.5	–314	–573
Desert	3699	–619	–630	–962	–980
Grassland	1923	380	969	694	810
Dry forest	1816	4	608	487	1296
Mesic forest	5172	561	–402	120	–519

OSU, Oregon State University; GFDL, Geophysical Fluid Dynamic Laboratory; GISS, Goddard Institute for Space Studies; UKMO, UK Meteorological Office.

Basically, boreal forest will be lost to other biomes (such as temperate forest) on its southern margins but will expand into tundra on its northern margins (Figure 8.2) (Chapin and Danell, 2001).

One biome that may suffer a particularly severe loss in area as a result of warming is arctic and alpine tundra. Indeed as the tree line moves up mountains and migrates northwards in the Northern Hemisphere, the extent of tundra will be greatly reduced, perhaps by as much as 55% in total (Walker et al., 2001). The alpine tundra zone may disappear completely from some mountain tops. Changes in the cryosphere will be considered in detail in Chapter 11.

Smith et al. (1992) attempted to model the response of Holdridge's Life Zones to global warming and associated precipitation changes as predicted by a range of different GCMs. These are summarized for some major biomes in Table 8.2. All the GCMs predict conditions that would lead to a very marked contraction in the tundra and desert biomes, and an increase in the areas of grassland and dry forests. There is, however, some disagreement as to what will happen to mesic forests as a whole, although within this broad class the humid tropical rainforest element will show an expansion.

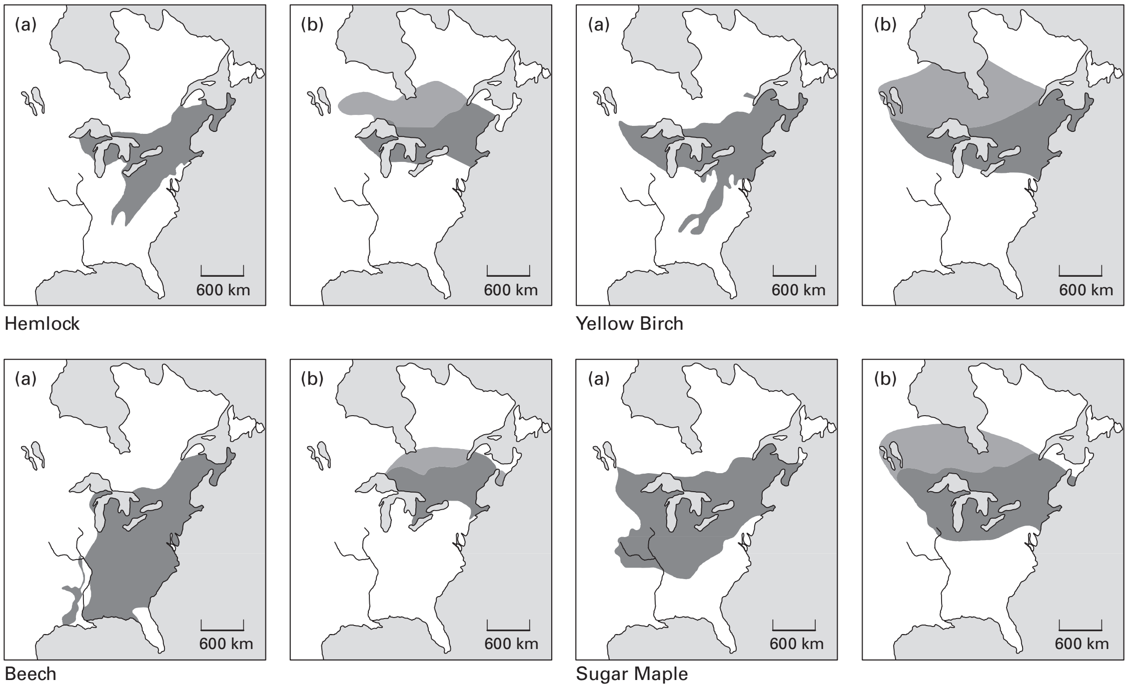

Figure 8.3 Present and future range of four tree species in eastern North America: (a) present range; (b) range in AD 2090 under the GISS GCM 2 × CO_2 scenario. The black area is the projected occupied range considering a rate of migration of 100 km per 100 years. The gray area is the potential projected range with climate change (after Zabinski and Davis, 1989).

Zabinski and Davis (1989) modeled the potential changes in the range of certain tree species in eastern North America, using a GISS GCM and a doubling of atmospheric carbon dioxide levels. The difference between their present ranges and their predicted ranges is very large (Figure 8.3).

Melillo et al. (2001) have modeled shifts in major vegetation types for the whole of the USA, using the Hadley (HadCM2) and Canadian Center for Climate Modeling and Analysis simulations and various biogeography models. The results of their simulations for 2099 are summarized in Table 8.3.

A somewhat precarious biome, located as it is at the southernmost tip of Africa and so with little scope for displacement, is the very diverse Fynbos Biome. It is a predominantly sclerophyll shrubland, characterized by the pre-eminence of hard-leaved shrubs, many of which are proteas. In addition to being extraordinarily diverse, this biome contains many endemic species. Modeling, using the Hadley Centre CM2 GCM, indicates a likely contraction of the extent of Fynbos by *c*. 2050 (Figure 8.4) (Midgley et al., 2003).

In the UK, the MONARCH programme (UK Climate Impacts Programme, 2001) has investigated potential changes in the distribution of organisms. Among the consequences of global warming they identify as being especially serious are the loss of montane heaths in the mountains of Scotland and the dieback of beach woodlands in southern Britain as summer droughts become more intense. However, it needs to be remembered that climate is not the only control on the distribution of species and that other factors such as biotic interactions and species' dispersal are also likely to be significant (Pearson and Dawson, 2003).

Vegetation will also probably be changed by variations in the role of certain extreme events that cause habitat disturbance, including fire, drought (Hanson and Weltzin, 2000), windstorms, hurricanes (Lugo, 2000), and coastal flooding (Overpeck et al., 1990). Other possible nonclimatic effects of elevated CO_2 levels on vegetation include changes in photosynthesis, stomatal closure and carbon fertilization (Idso, 1983), although these are still matters of controversy

Table 8.3 Projected changes in major vegetation types in the USA using the Hadley (HadCM2) and Canadian Center for Climate Modeling and Analysis simulations and various biogeography models (after Melillo et al., 2001)

Region	*Projected change*
Northeast	Under both simulated climates, forests remain the dominant natural vegetation, but the mix of forest types changes. For example, winter-deciduous forests expand at the expense of mixed conifer-broadleaf forests Under the climate simulated by the Canadian model, there is a modest increase in savannas and woodlands
Southeast	Under the climate simulated by the Hadley model, forest remains the dominant natural vegetation, but once again the mix of forest types changes Under the climate simulated by the Canadian model, all three biogeography models show an expansion of savannas and grasslands at the expense of forests. For two of the biogeography models, LPJ and MAPSS, the expansion of these nonforest ecosystems is dramatic by the end of the twenty-first century. Both drought and fire play an important role in the forest break-up
Midwest	Under both simulated climates, forests remain the dominant natural vegetation, but the mix of forest types changes One biogeography model, LPJ, simulates a modest expansion of savannas and grasslands
Great Plains	Under the climate simulated by the Hadley model, two biogeography models project an increase in woodiness in this region, while the third projects no change in woodiness Under the climate simulated by the Canadian model, the biogeography models project either no change in woodiness or a slight decrease
West	Under the climate simulated by both the Hadley and Canadian models, the area of desert ecosystems shrinks and the area of forest ecosystem grows
Northwest	Under both simulated climates, the forest area grows slightly

LPJ, Lund–Potsdam–Jena; MAPPS, Mapped Atmosphere–Plant–Soil System.

(Karnosky et al., 2001; Wullschleger et al., 2002; Karnosky, 2003). However, especially at high altitudes, it is possible that elevated CO_2 levels would have potentially significant effects on tree growth, causing growth enhancement (La Marche et al., 1984). Likewise, warm, drought-stressed ecosystems such as chaparral in the southwest USA might be very responsive to elevated CO_2 levels (Oechel et al., 1995).

Peterson (2000) has investigated the potential impact of climate change on the role of catastrophic winds from tornadoes and downbursts in causing disturbance to forests in North America. It is feasible that with warmer air masses over middle latitude areas the temperature contrast with polar air masses will be greater, providing more energy and thus more violent storms, but much more work needs to be undertaken before this can be said with any certainty.

The frequency and intensity of fires is an important factor in many biomes, and fires are highly dependent on weather and climate. Fires, for example, are more likely to occur in drought years or when there are severe lightning strikes. Wind conditions are also a significant control of fire severity. An analysis by Flannigan et al. (2000) suggests that future fire severity could increase over much of North America. They anticipate increases in the area burned in the USA of 25–50% by the middle of the twenty-first century, with most of the increases occurring in Alaska and the southeast USA.

Other disturbances to vegetation communities could be brought about by changing patterns of insects and pathogens (Ayres and Lombardero, 2000). For example, in temperate and boreal forests, increases in summer temperatures could accelerate the development rate and reproductive potential of insects, whereas warmer winter temperatures could increase overwinter survival. In addition, it is possible that the ranges of introduced alien invasive species could change (Simberloff, 2000).

It is still far from clear whether hurricane frequencies and intensities will increase in a warmer world. However, whether they increase or decrease, there are likely to be a number of possible ecosystem responses (Table 8.4).

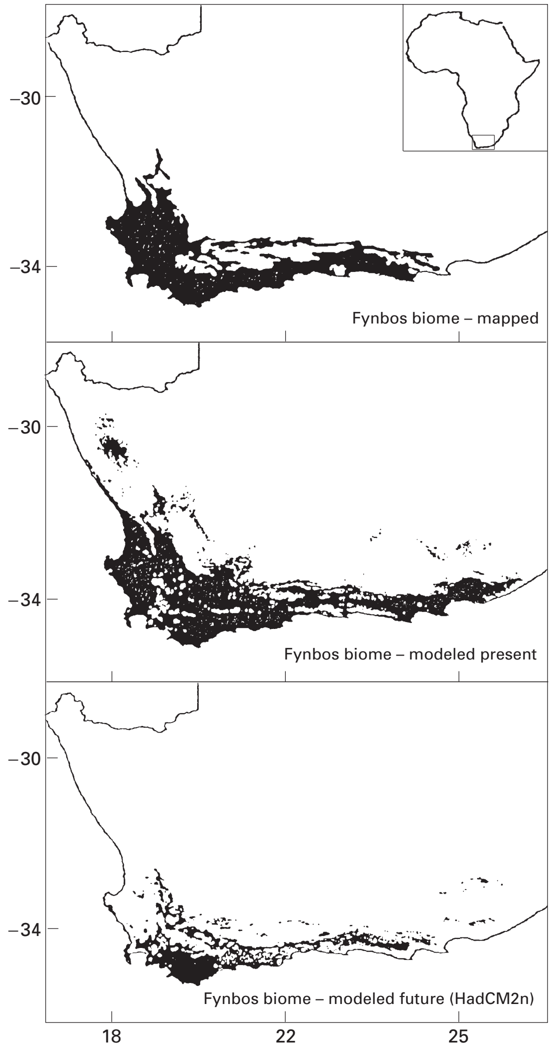

Figure 8.4 Current mapped Fynbos Biome (upper panel, after Rutherford and Westfall, 1994) and the modeled extent of the biome under current (middle panel) and future (*c*. 2050) climate conditions (lower panel), the latter based on climate change projections for the region generated by the GCM HadCM2. (Source: Midgley et al., 2003, figure 1.)

Climate and geomorphology

Attempts to relate landforms and land-forming processes to climatic conditions have been long continued and climatic geomorphology has a long and distinguished history (Stoddart, 1969; Derbyshire, 1973; Gutierrez-Elorza, 2001). Certainly, any change in climatic variability and extreme events would have considerable geomorphologic significance (Viles and Goudie, 2003) (Table 8.5).

It is self evident that some landforms and land-forming processes are intimately related to temperature. In general terms, for example, permafrost today occurs only in areas where the mean annual temperature is less than −2°C and it is virtually ubiquitous north of the −6 to −8°C isotherm in the Northern Hemisphere. Likewise, temperature is one of the major controls of ablation of glacier ice. At the other extreme, coral reefs have a restricted distribution in the world's oceans, which reflects their levels of temperature tolerance. They do not thrive in cool waters (i.e., < 20°C mean annual sea-surface temperature), but equally many coral species cannot tolerate temperatures greater than about 30°C, and have been stressed by warm El Niño–Southern Oscillation (**ENSO**) years.

Mangroves, important components of coastlines in the warmer parts of the world, are also sensitive to temperature. The best-developed mangrove swamps are found near the Equator where the temperature in the coldest month does not fall below 20°C in Indonesia, New Guinea, and The Philippines, and the number of species decreases with increasing latitude. Walter (1984) indicates that the last outposts of mangrove are to be found at 30°N and 33°S in Eastern Africa, 37–38°S in Australia and New Zealand, 20°S in Brazil and 32°N in the Bermudas. Mangroves in such areas might expand their poleward range under warmer conditions.

Some relatively clear relationships have also been established between precipitation levels and geomorphic processes and forms. Large sand dunes only occur under dry conditions where rainfall levels are less than 150–200 mm per year, and dust storms appear to be a feature of hyperarid areas where annual rainfall totals are around 0–150 mm per year. Desert crusts vary according to rainfall and according to the solubility of their components, with, for example, nitrate and halite crusts only occurring in the driest deserts and calcretes in areas where rainfall is less than around 500 mm per year.

However, for other phenomena the climatic controls may be rather more complex. Take, for example, the case of lake basins. Lake basins, and particularly those with no outlets, can respond in a dramatic manner to changes in their hydrological balance. During times of positive water budgets (due to high rates of water

Table 8.4 Potential response of ecosystems associated with changes in hurricane characteristics (modified after Lugo, 2000)

Increase in frequency and intensity	*Decreased in frequency and intensity*
A larger fraction of the natural landscape will be set back in successional stage, i.e., there will be more secondary forests	A larger fraction of the natural landscape will advance in successional stage, i.e., there will be more mature forests and fewer secondary forests
Forest aboveground biomass and height will decrease because vegetation growth will be interrupted more frequently or with greater intensity	Forest aboveground biomass and height will increase because the longer disturbance-free periods allow greater biomass accumulation and tree height
Familiar species combinations will change as species capable of thriving under disturbance conditions will increase in frequency at the expense of species that require long periods of disturbance-free conditions to mature	Species combinations will change as species capable of thriving under disturbance conditions will decrease in frequency and species typical of disturbance-free conditions will increase

Table 8.5 Examples of geomorphologic effects of decadal- to century-scale oscillations

Environment affected	*Impacts upon*
Terrestrial hydrology	Glacier mass balance Lake levels River flows Snow cover Permafrost
Terrestrial geomorphology	Soil erosion Floodplain sedimentation and erosion Slope instability/mass movements Dune movements Geochemical sediment growth Effects of fire frequency with knock-on effects on weathering Runoff and slope instability
Coastal/marine ecology and geomorphology	Coastal erosion Mangrove defoliation/land loss Coral bleaching Coastal dune activation

Table 8.6 Factors affecting rates of evaporation and runoff. Source: Bradley (1985)

Evaporation	*Runoff*
Temperature (daily means and seasonal range)	Ground temperature
Cloudiness and solar radiation receipts	Vegetation cover and type
Wind speed	Soil type (infiltration capacity)
Humidity (vapor pressure gradient)	Precipitation type (rain, snow, etc.)
Depth of water in lake and basin morphology (water volume)	Precipitation intensity (event magnitude and duration)
Duration of ice cover	Precipitation frequency and seasonal distribution
Salinity of lake water	Slope gradients (stream size and number)

input and/or low rates of evapotranspirational loss), lakes may develop and expand over large areas, only to recede and desiccate during times of negative water balance. Shoreline deposits and sediment cores extracted from lake floors can provide a detailed picture of lake fluctuations (e.g., Street and Grove, 1979). However, given the range of factors affecting rates of evaporation and runoff over a lake basin (Table 8.6) their precise climatological interpretation needs to be determined with care. A full review is provided by Mason et al. (1994).

Many of the studies of the links between climate and geomorphology have employed rather crude climatic parameters such as mean annual temperature or mean annual rainfall. It is, however, true that climatic extremes and climatic variability may be of even greater significance. Unfortunately, they are not dealt with very effectively in GCMs. We have imperfect knowledge of how extreme events and climate variability will change in a warmer world. It is, however, possible that climatic variability such as the ENSO

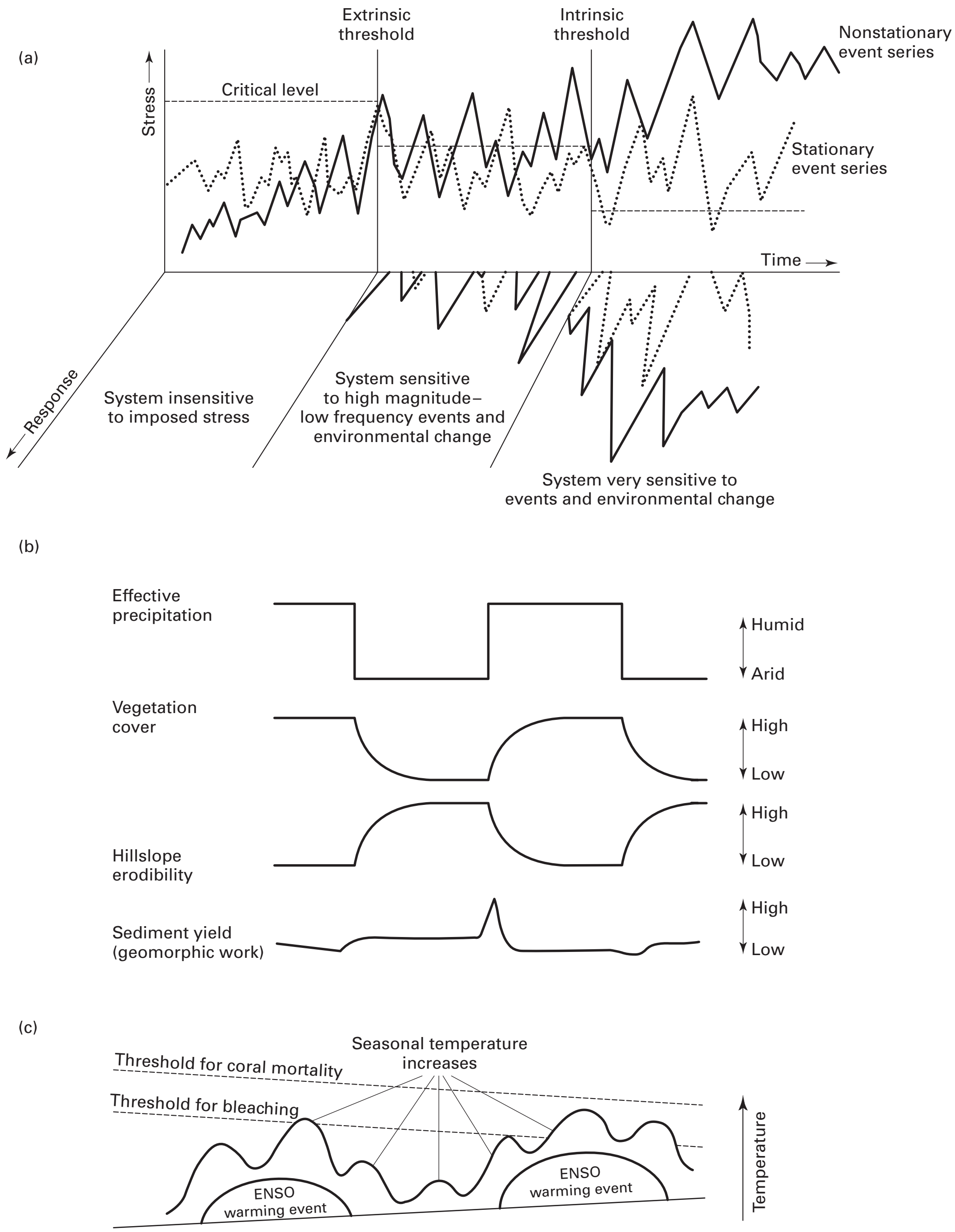

Figure 8.5 Representation of the impacts of climatic variability on geomorphic systems. (a) Stress–response sequences including thresholds under stable and changing climate conditions (adapted from Brunsden, 2001, figure 1). (b) A simplified view of the biogeomorphic response model (adapted from Knox, 1972 and Roberts and Barker, 1993, figure 6.1). (c) A model of the possible interactions of different timescales of warming and their impact on coral bleaching (adapted from Williams and Bunkley-Williams, 1990 and Viles and Spencer, 1995, figure 6.11).

phenomenon could be influenced by global warming, although Houghton et al. (2001: 151) draw no clear conclusions over this. Trenberth and Hoar (1997) thought the severe El Niño of 1997–1998 was perhaps enhanced by current global warming, and Timmerman et al. (1999) have modeled the way in which El Niño could be related to future global warming.

The ENSO and other modes of climatic variability, as has been pointed out by Douglas et al. (1999) in terms of their effects on geomorphology and ecology in the Danum Valley, Sabah, can produce a form of punctuated equilibrium in the landscape. Alternating periods of high geomorphic change (rhexistasie), followed by periods of stability in ecosystem and geomorphology (biostasie), seem to have occurred in the recent past at Danum Valley as a response to the changing rhythm of ENSO. Although the concepts of biostasie and rhexistasie are not new to geomorphology (having been introduced by Erhart (1956) and utilized by Knox (1993, 2001) amongst others), the recent discoveries of yet more modes of climatic variability, often with complex temporal rhythms, affecting large areas over long time spans make them ever more relevant. These ideas can also be linked to notions of complex response in the landscape (Brunsden, 2001), if we visualize change as a wave pulsing through a patchy landscape, with different areas possessing varied resistances to change. Thus, decadal climatic variability may set off a pulse of activity resulting in a complex landscape response. The impacts of climatic variability on ecological and geomorphic systems may be nonlinear, as recently found for rainfall erosivity and ENSO in the southwest USA (D'Odorico et al., 2001).

Several of these ideas on the clustering of events and complex responses to them can be presented as conceptual diagrams. Figure 8.5a indicates in a general way how clusters of climatic events can produce variable overtopping of geomorphic thresholds, although it represents a simple linear view of geomorphic response that may be an oversimplification for many geomorphic systems. Figure 8.5b illustrates how complex chains of linkages between climatic, vegetation and geomorphic processes produce a complex geomorphic response, and Figure 8.5c provides a simple conceptual model of the synergistic associations between different scales of warming producing **coral bleaching**. Such conceptual diagrams provide a useful starting point for analysing the relationships between climatic variability and geomorphology as a prelude to more detailed empirical and computational studies.

However, geomorphologists have long debated whether it is possible meaningfully to untangle the different roles of the various external forcing factors (climate, tectonics, and human activity) and internal factors (thresholds) in causing geomorphic response. Increasingly, many geomorphologists have come to suspect that this is a very difficult task because of the nonlinear, chaotic, and complex behavior of geomorphic systems.

In the following chapters we shall consider some of the challenges that face some major types of environment in the face of global warming and other trends that have been discussed in this brief introduction.

Points for review

How may vegetation belts respond to future climate changes?

Which landscape types may be especially sensitive to global warming?

Guide to reading

Arnell, N., 1996, *Global warming, river flows and water resources*. Chichester: Wiley. A study of potential future hydrological changes.

Chapin, F. S., Sala, O. E. and Huber-Sannwald, E. (eds), 2001, *Global biodiversity in a changing environment*. Berlin: Springer Verlag. A wide-ranging assessment of how biodiversity may change in response to climate and land use changes.

Eisma, D. (ed.), 1995, *Climate change. Impact on coastal habitation*. Boca Raton (Florida): Lewis Publishers. A study of the effects of climate change and sea-level rise.

Gates, D. M., 1993, *Climate change and its biological consequences*. Sunderland, Mass: Sinauer Associates. A textbook that considers some of the effects of climate change on the biosphere.

Houghton, J. D. and 7 others (eds), 2001, *Climate change 2001: the scientific basis*. Cambridge: Cambridge University Press. The IPCC report on global warming.

Leggett, J., 1996, *Climate change and the financial sector*. Munich: Gerling Akademie Verlag. A study of why climate change may have a severe impact on economies and business.