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Impacts of Climate Change on Mountain Regions

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EXECUTIVE SUMMARY

This chapter focuses on the impacts of climate change on physical, ecological, and socioeconomic systems in mountain regions; this topic was not addressed in the form of an explicit chapter in the 1990 Assessment Report.

Scenarios of climate change in mountain regions are highly uncertain; they are poorly resolved even in the highest-resolution general circulation models (GCMs). Furthermore, mountains perturb atmospheric dynamic and thermal characteristics, thereby establishing locally distinct, topographical microclimates that influence a wide range of environmental factors. With these facts in mind, we can summarize the effects of climate change on mountains as follows.

Mountain Physical Systems

If climate changes as projected in most climate scenarios, we have a high degree of confidence that the length of time that snow packs remain will be reduced, altering the timing and amplitude of runoff from snow, and increasing evaporation. These changes would affect water storage and delivery infrastructure around the world (see also Chapters 10 and 14). Alterations in precipitation regimes will modify these responses. Changes in extreme events (floods and droughts) could affect the frequency of natural hazards such as avalanches and mudslides. Downstream consequences of altered mountain hydrology are likely to be highly significant to economies dependent on this water.

Mountain Ecological Systems

We have a medium degree of confidence as to current understanding related to responses of mountain vegetation to changes in temperature and precipitation, based on paleoenvironmental studies, observations, and experiments. However, predictions of vegetation shifts are complicated by uncertainties in species-specific responses to increased CO_2 as well as uncertainties in projected regional temperature, precipitation, and soil moisture changes. All of these factors influence competitive interactions between species, particularly near ecotones such as timberline where species migrating upslope in response to warming are likely to encounter more slowly responding current inhabitants.

Human land use has contributed to diminished biological diversity in many mountain regions around the world. We have a medium degree of confidence as to the probability that climate change will exacerbate fragmentation and reduce key habitats. There is cause for concern that mountaintop-endemic species may disappear.

Mountain Socioeconomic Systems

In many developing countries, mountains provide food and fuel needed for human survival. We have a high degree of confidence that disruption of mountain resources needed for subsistence would have major consequences, but we have a medium degree of confidence as to the response of mountain populations to such changes.

In areas where people do not depend on mountain environments for subsistence, mountain lands are primarily used for cash crops, mining, timber harvest, and recreational activities. While not critical to human survival, these mountain areas are of increasing local and regional economic significance.

Mountains can be used effectively as conservation reserves in a changing climate because they support a relatively broad distribution of possible climates and a high diversity of habitats within a small physical area. Such reserves are most effective if they include a significant elevation range.

We are confident that competition between alternative mountain land uses is likely to increase under climate-change and population-rise scenarios.

5.1. Mountain Characteristics

5.1.1. *Introduction*

Mountain systems account for roughly 20% of the terrestrial surface area of the globe and are found on all continents. They are usually characterized by sensitive ecosystems and enhanced occurrences of extreme weather events and natural catastrophes; they are also regions of conflicting interests between economic development and environmental conservation. Once regarded as hostile and economically nonviable regions, mountains have attracted major economic investments for industry, agriculture, tourism, hydropower, and communication routes. Most mountain regions except in Antarctica are inhabited; Ives (1992) has pointed out that mountains provide the direct life-support base for about a tenth of humankind and indirectly affect the lives of more than half.

Despite their relatively small surface area, mountains are an integral part of the climate system. As a physical barrier to atmospheric flows, they perturb synoptic patterns and are considered to be one of the trigger mechanisms of cyclogenesis in mid-latitudes. Because of significant altitudinal differences, mountains such as the Himalayas, the Rockies, the Andes, and the Alps exhibit within short horizontal distances climatic regimes similar to those of widely separated latitudinal belts; they also feature increased diversity of species, communities, and habitats over lowland environments. Mountains are also a key element of the hydrological cycle, being the source of many of the world's major river systems. Abrupt changes in existing temperature and precipitation patterns that have led to the present distribution of vegetation, ice, snow and permafrost zones would impact heavily on the unique features of mountain environments. This, in turn, would lead to significant perturbations to the existing socioeconomic structures for populations living within the mountains themselves and indirectly to populations living outside these zones but dependent on them.

Mountains around the world are also significant to local and global economies because of the mineral and timber resources they contain, as well as their hydropower potential. Regional climate change could directly affect the viability and health of commercial timber production and, in an indirect manner, add cost to mining and other mineral extraction and processing activities in mountainous areas.

5.1.2. *Climate Characteristics*

A precise understanding of the climatic characteristics of mountain regions is limited by a lack of observations adequately distributed in time and space and insufficient theoretical attention given to the complex interaction of spatial scales in weather and climate phenomena in mountains (Beniston *et al.*, 1994). Meteorological research has tended to focus on the upstream and downstream influences of barriers to flow and on orographic effects on weather systems (Smith, 1979) rather than on microclimates within the mountain environments themselves. Climatic features relevant to mountain environments include microscale features of the atmosphere that are superimposed on larger scales of motion and the influence of elements of the surface, such as vegetation and geomorphologic features, which can create microclimatic contrasts in surface heating, soil moisture, or snow-cover duration (Geiger, 1965). Isolating macro- and microscale processes in order to determine their relative importance is complicated by inadequate databases for most mountain areas of the world (Barry, 1994).

Four principal factors influence mountain climates—namely, altitude, continentality, latitude, and topography. The role of these factors is summarized schematically in Table 5-1 (from Barry, 1992); the effects refer to responses to an increase in the factor listed. These climatic differences, in turn, influence vegetation type and cover, hydrology, and sometimes geomorphic features. In particular, vegetation distribution in mountain regions is so closely linked to climatic parameters that vegetation belt typology has been widely used to delineate climate influences (Troll, 1968; Lauer, 1979; Monasterio, 1980; Quezel and Schevok, 1981; Klötzli, 1984, 1991, 1994;

***Table 5-1:** Climatic effects of the basic controls of mountain climate.*

Factors	Primary Effects	Secondary Effects
Altitude	Reduced air density, vapor pressure; increased solar radiation receipts; lower temperatures	Increased wind velocity and precipitation (mid-latitudes); reduced evaporation; physiological stress
Continentality	Annual/diurnal temperature range increased; cloud and precipitation regimes modified	Snow line altitude increases
Latitude	Daylength and solar radiation totals vary seasonally	Snowfall proportion increases; annual temperatures decrease
Topography	Spatial contrasts in solar radiation and temperature regimes; precipitation as a result of slope and aspect	Diurnal wind regimes; snow cover related to topography

Ozenda, 1985; Quezel and Barbero, 1990; Rameau *et al.*, 1993). Although it would appear simple to discuss how these typologies might be modified as a result of changing global climate, the climate system and its interaction with such landscape components as vegetation, geology, topography, and soil are highly nonlinear (Beniston, 1993, 1994).

5.1.3. Physical Characteristics

The various components of the hydrologic cycle are critical links between climate and the life of mountain communities and also influence areas downstream. The timing and volume of rainfall and snowmelt are critical constraints on hydrological systems. Sediment loadings can be exceptionally high in many rivers originating in mountains and reflect geomorphologic processes. Unless slowed down by major lakes within mountains themselves or in adjacent lowlands, or by engineering works designed to control torrent flows, rivers will carry their heavy loads unimpeded into the plains. This can be beneficial for agriculture because these sediments create rich and fertile soils, but excessive loads can have adverse consequences, such as flooding of populated lowland areas.

Influencing the hydrological system are elements of the mountain cryosphere, particularly glaciers and seasonal snow packs. These are of major significance in some of the more elevated mountain chains of the world in terms of water availability in the source region of many of the world's rivers (Steinhauser, 1970). Snow cover in mountains is affected by the following factors, which are all linked to climate:

- Snow cover duration, which has been shown to vary linearly with altitude and is a function of slope orientation (Slatyer *et al.*, 1984)
- Snow depth, which also varies with altitude, orientation, and topography (Witmer *et al.*, 1986; Föhn, 1991)
- Snowmelt runoff, which feeds into the hydrologic system of mountains; this is determined by temperatures and surface energy balance in spring (Collins, 1989; Chen and Ohmura, 1990).

Changes in glacier and permafrost ice are linked to changes in the energy balance at the Earth's surface. Rates of such glacier and permafrost changes can be determined quantitatively over various time intervals, allowing direct comparison with estimated effects of anthropogenic greenhouse forcing (Haeberli, 1994). As a consequence, they are among the clearest signals evident in nature of ongoing warming trends related to the enhanced greenhouse effect (Haeberli, 1990; Wood, 1990; WGMS, 1993). Evidence from borehole profiles in permafrost also helps to determine the rate and magnitude of temperature changes (Mackay, 1990, 1992; Vonder Muehll and Holub, 1995).

A major problem in many mountain regions related to climate change is increased erosion and reduced slope stability. The combination of complex orography with steep slopes, intense rainstorms, and, in some regions, frequent earthquakes, causes a high proportion of mass movement, which eventually finds its way into rivers as heavy sediment load. Any changes to an already fragile environment would impact heavily on geomorphologic processes, resulting in indirect impacts to natural and socioeconomic systems (Innes, 1985). For example, higher precipitation, particularly during extreme events, can augment the risk of erosion. However, the potential for increased erosion depends on a number of other factors linked to topography, geology, soil types, and farming and conservation practices associated with a particular region. Enhanced precipitation can sometimes favor the development of denser vegetation, which in turn prevents soils from being eroded. Precipitation is not only a water source in mountain terrain but also the trigger factor for the occurrence of debris flow, landslide, and slope failure. No general study of the relationship between rainfall and landslides exists at a global scale, but in many specific cases a clear relation has been established between rain duration and induced movements (Noverraz and Bonnard, 1992). Relations between rainfall and induced movements can be direct and immediate or more long-term; in many cases, a long period of rainfall prior to the event has to be taken into account to explain a particular landslide (Bonnard, 1994).

5.1.4. Ecological Characteristics

Altitudinal vegetation distribution has traditionally been used to characterize mountain environments. This distribution is

Box 5-1. Climate Variabilty as Reflected in Glacier Regimes
in the Former Soviet Union (FSU)

Solomina (1995) presents case studies of glacier fluctuations in the FSU. Major conclusions include:

- The length of many mountain glaciers in the FSU has decreased by up to 4 km during the last two centuries. The maximum degradation has occurred in regions with strong glaciation (the Caucasus, Pamirs, Tien Shan, and Altay).
- Changes in the equilibrium line altitude (ELA: the altitude of a glacier at which snow accumulation is equal to snow ablation) have also been more pronounced in regions with large glaciers, namely the Caucasus, Altay, and the periphery of the Central Asian mountains, and less in other mountain zones of the FSU. The mean ELA is estimated as being 50–80 m lower today than during the Little Ice Age.

strongly influenced by climatic parameters, but not exclusively. Topography, edaphic factors, and, in many areas, human activities and the disturbances they generate strongly interfere with the potential distributions suggested by large-scale climatic parameters alone.

The zonation patterns of vegetation differ according to the location of the mountains along a latitudinal gradient, as shown in Figure 5-1. Tropical mountains typically experience relatively uniform mean temperatures throughout the year, with significant diurnal temperature variation. Mountains in temperate and boreal zones, on the other hand, are characterized by seasonal climates with a well-defined growing season, whereby plants can exploit the short, warm summers. Many plant species at high altitudes are capable of surviving harsh conditions as a result of the onset of a hardening process.

The amount and duration of snow cover influences high mountain vegetation by determining growing season and moisture conditions. In the alpine zones, exposed, windy ridges are generally covered with xeric dwarf shrubs and wind-hardy lichens. Depending on nutrition and soil moisture, more mesic dwarf shrub heaths and mesic low herb meadows are found on lee slopes of intermediate snow cover. The late-exposed snow patches have hygrophilous herb communities. Vascular plants may be completely lacking due to the very short growing season.

Both altitude and latitude contribute to high diversity in species composition in mountain forests: Coniferous trees are common in boreal and temperate mountains, sclerophylous types in Mediterranean zones, deciduous species in oceanic boundaries of continents (e.g., Norway, British Columbia), and ericaceous (East Africa; Hedberg, 1951) or podocarp (Equatorial Andes) species in tropical zones. Furthermore, a unique feature of tropical mountains are cloud forests, which exhibit a high degree of biodiversity.

5.1.5. *Human Characteristics*

Mountains having a history of relatively dense settlement, such as those in Europe, Japan, and the eastern United States, are facing a decline of traditional agriculture and forestry, which have been economically viable only because of government subsidies. Mountains with a history of less dense settlement, such as the western United States, Canada, South America, Africa, Australia, and New Zealand, have over the past three centuries faced pressure from colonization and immigration, which have introduced scattered but growing settlements. In relatively recent decades, tourism has emerged as a significant income source in mountain regions, as well as a major source of environmental stress (Grötzbach, 1988). While in some regions (e.g., western Europe and Japan) mountains are experiencing depopulation (Yoshino *et al.*, 1980; Price, 1994), in general, land-use pressures are increasing because of competition between refuge use, mineral extraction and processing, recreation development, and market-oriented agriculture, forestry, and livestock grazing (Ives and Messerli, 1989; Messerli, 1989).

Mountain habitats in developing nations, where traditional subsistence agriculture continues, face stress from increasing human population, ameliorated to some extent by short-term or seasonal migration. In many of these regions, pressures exist to develop market-based agricultural systems, changing from a largely local economy to a national and international one. In Africa, most of the mid-elevation ranges, plateaus, and slopes of high mountains are under considerable pressure from commercial and subsistence farming activities (Rongers, 1993). In

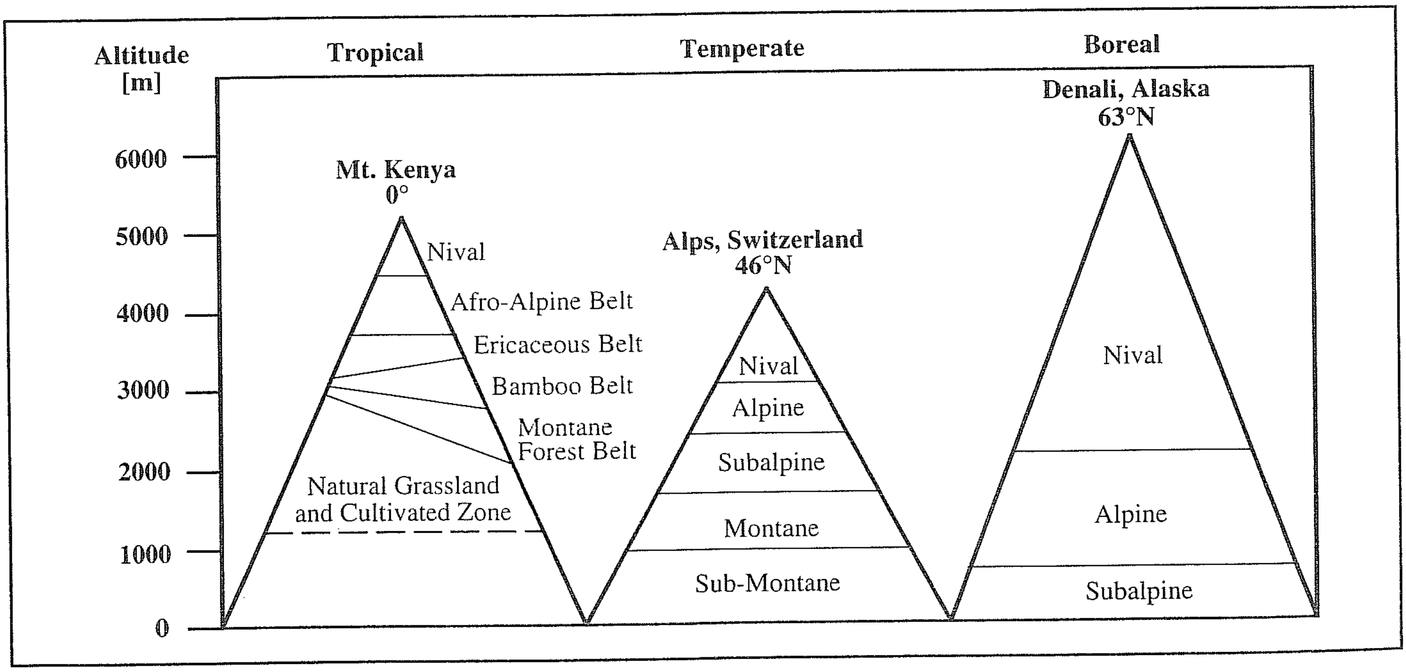

Figure 5-1: Schematic illustration of vegetation zonations in tropical, temperate, and boreal mountains.

Box 5-2. Socioeconomic Characteristics of North American Mountain Regions

The major mountains of North America are the Rockies, the eastern Appalachian chain, and various coastal ranges along the west coast of the continent. Primarily in the United States and in Mexico, the mountains border on semi-arid, highly populated urban areas (Mexico City, Los Angeles, Denver); most North American mountains are sparsely populated, however. Traditional economies have been in the mining and pastoral fields, with limited agriculture where the climate allows it. Forest harvest and replanting has been practiced in many areas. Much of the remaining area, especially in the Western United States and Canada, is set aside for wilderness, where human influence is minimized, and for parks, which are managed (Peine and Martinka, 1992). Because of this rather significant wilderness designation (over 16 million hectares, about 6% of all forested lands in the United States alone), adaptation to the potential impact of global climate change on natural ecosystems and biological diversity is more an administrative management issue than a scientific one (OTA, 1993). One problem is that wilderness areas tend to occupy only the tops of mountains, not the entire mountain, limiting the availability of diverse habitats and hence migration opportunities.

unprotected areas, mountain forests are cleared for cultivation of high-altitude adapted cash crops like tea, pyrethrum, and coffee. Population growth rates in East Africa, among the highest in the world (Goliber, 1985), are concentrated in agriculturally fertile and productive mountain districts (Government of Tanzania, 1979). This is quite evident near Mt. Kenya, Mt. Kilimanjaro, and in the Usambara Mountains (Lundgren, 1980). Tourism is becoming economically important in small, well-defined portions of these regions (Price, 1993).

Particularly in tropical and semi-arid climates, mountain areas are usually wet, cool, and hospitable for human dwelling and commercial cultivation. Human encroachment on mountain regions has reduced vegetation cover, thus increasing soil-moisture evaporation, erosion, and siltation, and thereby adversely affecting water quality and other resources. Impact analyses need to seriously consider not only climate but also the direct anthropogenic influence on mountain regions.

5.2. Impacts of Climate Change

Mountain environments are potentially vulnerable to the impacts of global warming because the combination of enhanced sensitivity to climatic change and limited possibilities for species migration to favorable locations make mountains "islands" in a "sea" of surrounding ecosystems (Busby, 1988). This vulnerability has important ramifications for a wide variety of human uses and natural systems, such as nature conservation, land management, water use, agriculture, and tourism. It also has implications for a wide range of natural systems (hydrology, glaciers and permafrost, ecosystems, and so forth).

Few assessments of the impacts of climate change have been conducted in mountain regions, in contrast to other biomes such as tropical rainforests, coastal zones, and high-latitude or arid areas. There are a number of reasons to explain this, some of which are listed below:

- The dominant feature of mountains (i.e., topography) is so poorly resolved in most general circulation climate models (GCMs) that it is difficult to use GCM-based scenarios to investigate the potentia impacts of climate change. There also is a significan lack of comprehensive multidisciplinary data for impac studies, which is one of the prerequisites for case studies of impacts on natural or socioeconomic system (Kates *et al.*, 1985; Riebsame, 1989; Parry *et al.*, 1992)
- The complexity of mountain systems presents majo problems for assessing the potential impacts of climate change. This applies to assessments of change in both biophysical systems (e.g., Rizzo and Wiken 1992; Halpin, 1994) and societal systems, the latter in particular because it is difficult to quantify the value of mountain regions in monetary terms (Price, 1990)
- Tourism, which is an increasingly important component of mountain economies, is not an easily defined economic sector and is highly influenced by factors other than climate change.

5.2.1. *Scenarios and Methodologies*

Mitigation and adaptation strategies to counteract possible consequences of abrupt climate change in mountain regions require climatological information at high spatial and temporal resolution. Unfortunately, present-day simulation techniques for predicting climate change on a regional scale are by no means satisfactory. This is because GCMs generally operate with a rather low spatial resolution over the globe (~300 km) in order to simulate climate trends over a statistically significant period of time. As a result, entire regions of sub-continental scale have been overlooked in terms of their climatological specificities, making it difficult to predict the consequences of climate change on mountain hydrology, glaciers, or ecosystems in a specific mountain region (Giorgi and Mearns, 1991; Beniston, 1994). The situation is currently improving with the advent of high-resolution climate simulations in which the spatial scale of GCMs is on the order of 100 km (Beniston *et al.*, 1995; Marinucci *et al.*, 1995). However, even this resolution is generally insufficient for most impact studies.

A number of solutions exist to help improve the quality of climate data used in impact assessments and economic decisionmaking.

Options include statistical techniques of downscaling from synoptic to local atmospheric scales (Gyalistras *et al.*, 1994); coupling of mesoscale, or limited area, models (LAMs) to GCMs (Giorgi *et al.*, 1990, 1992; Marinucci and Giorgi, 1992; Marinucci *et al.*, 1995); and use of paleoclimatic and geographical analogs (e.g., LaMarche, 1973; Webb *et al.*, 1985; Davis, 1986; Schweingruber, 1988; Graumlich, 1993; Luckman, 1994).

Any meaningful climate projection for mountain regions—and, indeed, for any area of less than continental scale—needs to consider processes acting on a range of scales, from the very local to the global. The necessity of coupling scales makes projections of mountain climates difficult.

5.2.2. Impacts on Physical Systems

5.2.2.1. Impacts on Hydrology

In spite of limitations in the quality of historical data sets and inconsistencies in projections between GCMs, particularly for precipitation (Houghton *et al.*, 1990), assessments of the potential impacts of climate change on water resources, including snowfall and storage, have been conducted at a variety of spatial scales for most mountain regions (Oerlemans, 1989; Rupke and Boer, 1989; Lins *et al.*, 1990; Slaymaker, 1990; Street and Melnikov, 1990; Nash and Gleick, 1991; Aguado *et al.*, 1992; Bultot *et al.*, 1992; Martin, 1992; Leavesley, 1994). For example, high-resolution calculations for the Alps (Beniston *et al.*, 1995) using a nested modeling approach (GCM at 1° latitude/longitude resolution coupled to a LAM at 20-km resolution) indicate that in a doubled-CO_2 atmosphere wintertime precipitation will increase by about 15% in the Western Alps; this is accompanied by temperature increases of up to 4°C. Summertime precipitation generally decreases over the alpine domain, with July temperatures on average 6°C warmer than under current climatic conditions. Such numerical experiments, while fraught with uncertainty, nevertheless provide estimates of possible future regional climatic conditions in mountains and thereby allow more detailed impact assessments.

Climate change may be characterized by changes in seasonal or annual precipitation, proportions of solid to liquid precipitation, or frequencies of extreme events. Whatever the directions and magnitudes of change, mountain communities and those downstream need to be prepared to implement flexible water management strategies that do not assume that recent patterns will continue. Events in recent history may provide useful guidelines for developing such strategies (Glantz, 1988).

Climate-driven hydrology in mountain regions is determined to a large extent by orography itself; mountain belts produce regional-scale concentration of precipitation on upwind slopes and rain-shadow effects in the lee of mountains and in deep intermontane valley systems, often giving rise to high mountain deserts. Many of the more elevated mountain chains of the world intercept large atmospheric moisture fluxes and produce belts of intense precipitation. Along the southern slopes of the Himalayas, enhancement of monsoonal conditions results in some of the highest annual average precipitation in the world, such as at Cherrapunji, India. The spectrum of variability of hydrological regimes ranges from the predominantly rainforested slopes of Papua-New Guinea to the ice fields of the Patagonian Andes. Climate change will affect the relative importance of these two extreme regimes, as well as the total moisture flux and how it is delivered temporally. Mountains such as the Andes and the Himalayas are source regions for some of the world's largest rivers, such as the Amazon, the Ganges, Irrawady, and Yangtse, and the discharge characteristics of these rivers and their shifts under changed climatic conditions will be largely governed by modified precipitation regimes.

5.2.2.2. Impacts on Mountain Cryosphere

The effects of temperature and precipitation changes on glaciers are complex and vary by location. In polar latitudes and at

Box 5-3. Estimates of Cryosphere Response to Climate Change in Asian, Latin American, and African Mountain Chains

Wang (1993) estimates that about 21% of the glacial area will disappear in Northwest China if temperature increases by 1–1.3°C and precipitation decreases by 60–80 mm. Glaciers with areas of less than 0.5 km^2 in the Tianshan and Qilian ranges and permafrost areas in Northeast China and Qing-Zang plateau are expected to disappear if temperature increases by 2°C or more (Zhang, 1992; Wang, 1993).

In the Venezuelan Andes, photographs from 1885 show that the present-day snowline has risen from 4,100 m to more than 4,700 m (Schubert, 1992). These changes in ice extent and in snowline altitude have had important geoecological effects, leading to shifts in vegetation belts and to the fragmentation of previously continuous forest formations. Enhancement of the warming signal in these regions would lead to the disappearance of significant snow and ice surfaces.

On Mount Kenya, the Lewis and Gregory glaciers have shown recession since the late 19th century. Calculations of area and volume loss of the Lewis Glacier for 1978–90 show similar rates to those of the preceding decades. Nevertheless, Hastenrath and Rostom (1990) propose that the retreat in the late 19th century was triggered by a decrease in cloudiness and precipitation, whereas the retreat since the 1920s may be due to an observed warming trend.

very high altitudes of mid-latitudes, atmospheric warming does not directly lead to mass loss through melting/runoff but to ice warming (Robin, 1983). In areas of temperate ice, which predominate at lower latitudes or altitudes, atmospheric warming can directly impact the mass and geometry of glaciers (Haeberli, 1994).

Haeberli (1994) indicates that alpine glacier and permafrost signals of warming trends constitute some of the clearest evidence available concerning past and ongoing changes in the climate system. The glacier fluctuations, in particular, indicate that the secular changes in surface energy balance may well be in accordance with the estimated anthropogenic greenhouse forcing. In fact, the evidence strongly indicates that the situation is now evolving at a high and accelerating rate beyond the range of Holocene (natural) variability. Temperature profiles from permafrost boreholes also confirm the nature of recent warming trends (Vonder Muehll and Holub, 1992; Mackay, 1990, 1992).

In terms of climate-change impacts on snow, Föhn (1991) suggests that one potential effect of global warming in the European Alps might be a delay in the first snowfall and a reduction in the length of snow cover. Analysis of satellite data from the 1980s and early 1990s has shown that lowlands around the Alps experience about 3–4 weeks less snow cover than they historically have had (Baumgartner and Apfl, 1994); this tendency will likely accelerate in a warmer climate. Additionally, snow accumulation and ablation exhibit different temporal patterns than in the past and could be even more irregular in a changed climate. For higher elevations, the total annual snow volume accumulated during the winter has not changed significantly this century, despite the observed global temperature rise.

Investigations concerning the impact of climate change on snow conditions in the French Alps were undertaken with a physically based snow model (CROCUS) coupled to a meteorological analysis system (SAFRAN). The two systems have been validated by comparing measured and simulated snow depth at 37 sites of the area for the period 1981/1991. Sensitivity studies show that lower elevations (i.e., below 1500 m) are extremely sensitive to small changes in temperature, especially in the southern part of the French Alps. Variations of precipitation amount influence the maximum snow depth (or snow water equivalent) much more than snow cover duration (Martin, 1995).

Reduced snow cover will have a number of implications; it will increase early seasonal runoff, leading to drier soil and vegetation in summer and greater fire risk. Further details on impacts on mountain cryosphere are provided in Chapter 7.

5.2.2.3. *Impacts on Extreme Events*

It is uncertain whether a warmer global climate will be accompanied by more numerous and severe episodes of extreme events because current GCM capability to simulate extremes and their altered frequency of occurrence in a changed climate is extremely limited. Enhanced occurrences of intense storms, accompanied by high precipitation and/or winds, woul inevitably have significant repercussions on a number of sensitive environmental and socioeconomic systems. If the severit of storms such as "Vivian" (European Alps, 1990, whic destroyed vast areas of forested slopes) or the intense precipitation of August 1987 in central Switzerland (which disrupted ra and road traffic in the Gotthard Region, one of the major communication routes across the Alps) were to increase in frequency in a changed climate, populations living in mountains woul be faced with significant social and economic hardships.

Other impacts associated with extreme events include fire Forest fires are likely to increase in places where summer become warmer and drier, as has been projected for the Alps, fo example (Beniston *et al.*, 1995). Prolonged periods of summe drought would transform areas already sensitive to fire int regions of sustained fire hazard. The coastal ranges o California, the Blue Mountains of New South Wales (Australia) Mt. Kenya, and mountains on the fringes of the Mediterranea Sea, already subject to frequent fire episodes, would be severely affected. There would be major socioeconomic impacts a well, because many sensitive regions are located close to majo population centers (e.g., Los Angeles and the Bay Area i California; the Sydney conurbation in Australia; coastal resort close to the mountains in Spain, Italy, and southern France).

5.2.2.4. *Impacts on Geomorphologic Processes*

The latitude and altitude of different mountain systems determine the relative amount of snow and ice at high elevation and intense rainfall at lower elevations. Because of the amoun of precipitation and relief, and the fact that many of thes mountains are located in seismically active regions, the adde effect of intense rainfall in low- to middle-altitude regions is t produce some of the highest global rates of slope erosion Climate change could alter the magnitude and/or frequency o a wide range of geomorphologic processes (Eybergen an Imeson, 1989). The following examples provide an indicatio of the nature of the changes that might occur with specifi changes in climate.

Large rockfalls in high mountainous areas often are caused b groundwater seeping through joints in the rocks. If average an extreme precipitation were to increase, groundwater pressur would rise, providing conditions favorable to increased triggering of rockfalls and landslides. Large landslides are propagated by increasing long-term rainfall, whereas small slides ar triggered by high intensity rainfall (Govi, 1990). In a future climate in which both the mean and the extremes of precipitatio may increase in certain areas, the number of small and larg slides would correspondingly rise. This would contribute t additional transport of sediments in the river systems originating in mountain regions. Other trigger mechanisms for rockfalls are linked to pressure-release joints following deglaciation (Bjerrum and Jfrstad, 1968); such rockfalls may b observed decades after the deglaciation itself, emphasizing th long time-lags involved. Freeze–thaw processes also are ver

Box 5-4. Long-Term Records of Climate and Vegetation Dynamics: A Key to Understanding the Future

Paleoenvironmental records represent the only available source of information on the long-term natural variability within the biosphere-atmosphere system. The spatial and temporal resolution of paleoenvironmental data sets has increased in recent decades on annual to millenium scales, and data reflecting vegetation dynamics are now available for many parts of the world (Bradley and Jones, 1992; Wright *et al.*, 1993; Graumlich, 1994). In addition, comparisons of records of past vegetation dynamics to paleoclimatic simulations by GCMs have improved the understanding of the role of climate in governing past vegetation change (Webb *et al.*, 1993). Several major findings of paleoresearch have guided investigations of the effects of future climate change on the Earth's biota. These include changing seasonality, which may result in unexpected vegetation patterns (Prentice *et al.*, 1991); rapid changes in both climate and vegetation with ecosystem-wide implications (Gear and Huntley, 1991); and short-term extreme events that may impact tree population structures (Lloyd and Graumlich, 1995). Thus, the same types of individualistic behavior of species observed in physiological attributes are mirrored in long-term and large-scale vegetation dynamics (Graumlich, 1994).

Future climates are likely to be characterized by combinations of temperature and precipitation that are not replicated on the contemporary landscape. Any predictions of vegetation response to climatic changes must be based on an improved understanding of the relationship between climatic variation and vegetation processes; this is where analyses of high-resolution proxy data can be of use.

important (Rapp, 1960), and several authors have reported possible links between rockfall activity and freeze–thaw mechanisms linked to climate change (Senarclens-Grancy, 1958; Heuberger, 1966).

A further mechanism that would be responsible for decreased slope stability in a warmer climate is the reduced cohesion of the soil through permafrost degradation (Haeberli *et al.*, 1990; see also Chapter 7). With the melting of the present permafrost zones at high mountain elevations, rock and mudslide events can be expected to increase in number and possibly in severity. This will certainly have a number of economic consequences for mountain communities, where the costs of repair to damaged communications infrastructure and buildings will rise in proportion to the number of landslide events. In many mountainous regions, tourist resorts such as those in the Alps and the Rocky Mountains or large urban areas close to mountains (suburbs of South American Andean cities, Hong Kong, or Los Angeles, for example) have spread into high-risk areas, and these will be increasingly endangered by slope instability.

5.2.3. *Impacts on Ecological Systems*

While the authors acknowledge that climatic change on fauna will be important, priority is given here to vegetation response, particularly because vegetation dynamics will determine future distributions of animal habitats (both directly for herbivores and indirectly for predators).

The potential impacts of future climatic changes on mountain ecosystems and nature reserves have become an increasingly important issue in the study of long-term biodiversity management and protection (Peters and Darling, 1985; McNeely, 1990; Halpin, 1994; OTA, 1993). Projected changes in global temperatures and local precipitation patterns could significantly alter the altitudinal ranges of important species within existing mountain belts and create additional environmental stresses on already fragile mountain ecosystems (Guisan *et al.*, 1995).

On a global scale, plant life at high elevations is primarily constrained by direct and indirect effects of low temperature and perhaps also by reduced partial pressure of CO_2. Other atmospheric influences, such as increased radiation, high wind speeds, or insufficient water supply may come into play, but only on a regional scale (Lüdi, 1938; Fliri, 1975; Lauscher, 1977; Körner and Larcher, 1988; Barry, 1992). Plants respond to these climatological influences through a number of morphological and physiological adjustments, such as stunted growth forms and small leaves, low thermal requirements for basic life functions, and reproductive strategies that avoid the risk associated with early life phases.

5.2.3.1. *Inference from the Past*

Paleoenvironmental information, including tree-ring data and pollen loadings, serves as an indicator of past climate-vegetation relationships. Paleoecology offers insights into the nature of climate-vegetation interactions. The indirect record of the response of organisms to environmental changes of the past is equivalent to results from natural, if unplanned, experiments (Davis, 1989). Because these natural experiments typically include conditions not observed in the 20th century, the paleorecord documents biotic responses to a substantially broader range of environmental variations than can be obtained through observations.

Paleoecological and paleoclimatic studies are of key importance in establishing baselines and are the only means available for determining amplitudes and rates of change of vegetation to natural climate variations. In addition, paleoenvironmental data are essential for model simulations and scenario generation.

5.2.3.2. Ecophysiological Responses

It is known from both common sense and paleoenvironmental research that plant communities respond to a general increase in temperature through a shift toward higher latitudes and altitudes. However, this shift is controlled by ecophysiological processes at the individual plant level, involving direct and indirect effects of temperature increase, photoperiod constraints, and competition processes.

Callaghan and Jonasson (1994) show that direct effects of increased temperature on aboveground processes tend to dominate over indirect effects on belowground processes and that these will be greatest at locations where current climates are extreme (Bugmann and Fischlin, 1994). Reduced duration of snow cover is likely to be important for vegetation in a warmer climate (Körner, 1994).

Heide and coworkers have clearly shown that photoperiod constraints in cold climates may be strong and of overriding importance (Heide, 1985; Solhaug, 1991). For most native species, the precise photoperiodic requirements and their interaction with temperature are not known, thus making it difficult to estimate plant migration based on temperature scenarios alone (Ozenda and Borel, 1991). According to Heide (1989, 1990), some alpine grasses have no photoperiod requirements for initiating growth and are therefore affected by spring frosts. For example, in northern Sweden, Molau (1993) has shown that increased length of the growing season and increased summer temperature are the two components of climate change that will have the greatest impact on reproduction and population dynamics in arctic and alpine plants.

If climatic change leads to warmer and locally drier conditions, mountain vegetation could suffer as a result of increased evapotranspiration. This is most likely for continental and Mediterranean mountains. A change in regional distribution of air humidity could strongly modify the tree species composition of mountain forests; drier conditions, for example, would give continental species an advantage. If changes in water supply were to occur during summer, they would also become effective indirectly by influencing topsoil processes and plant nutrition (Bowman *et al.*, 1993; Baron *et al.*, 1994). When temperatures are low, microbial activity in alpine soils is concentrated in the top few centimeters. This is the part of the soil where nutrient recycling and most of the root growth takes place; when this top layer desiccates, mineral cycling is blocked (Körner, 1989). Regular rainfall is thus a prerequisite for plant nutrition. Because most alpine plants are inherently slow growers, any enhancement of nutrient supply will stimulate the few potentially fast-growing species in a community, eliminate others, and thus cause substantial changes in vegetation structure.

The length and depth of snow cover, often correlated with mean temperature and precipitation, is one of the key climatic factors in alpine ecosystems (Barry and Van Wie, 1974; Aulitzky *et al.,* 1982; Ozenda, 1985; Burrows, 1990; Musselmann, 1994). Snow cover provides frost protection fo plants in winter and water supply in spring. Alpine plant communities are characterized by a very short growing season (i.e. the snow-free period) and require water to commence growth Ozenda and Borel (1991) predict that the most threatened vegetation communities will be those that live in snow beds and i hollows because these groups are subjected to summer drying

5.2.3.3. Geographical Distribution and Migratory Response

A general hypothesis presented by Peters and Darling (1985 and others concerns the potential movement of the climati ranges of species along altitudinal, thermally defined gradients This conceptual model implies that the boundaries of presen species' climatic ranges will respond symetrically to changes i temperature related to the adiabatic lapse rate for a particula mountain site. The general biogeographical rule used to deriv this conceptual model is attributed to the "Hopkins bioclimati law" (MacArthur, 1972; Peters and Darling, 1985), whic relates a 3°C change in temperature to a 500 m change in altitude. According to this conceptual model, the expected impact of climate change in mountainous nature reserves woul include the loss of the coolest climatic zones at the peaks of th mountains and the linear shift of all remaining vegetation belt upslope. Because mountaintops are smaller than bases, the present belts at high elevations would occupy smaller and smalle areas, and the corresponding species would have smaller populations and might thus become more vulnerable to genetic an environmental pressure (Peters and Darling, 1985; Hansen-Bristow *et al.*, 1988; Bortenschlager, 1993).

Examples of past extinctions attributed to upward shifts ar found in Central and South America, where vegetation zone have moved upward by 1000–1500 m since the last glacia maximum (Flenley, 1979; van der Hammen, 1974). Romm and Turner (1991), in their study on possible implications o climate change for ecosystems in Yellowstone National Par (USA), project species extinctions as a result of fragmentatio and shrinking mountaintop habitats.

In the Alps, the main climatic space contraction and fragmentation of plant populations would be in the present alpine and nival belts, where rare and endemic species with low dispersal capacities could become extinct. Because the alpine belt contains a non-negligible part of the endemic alpine flora (15%; Ozenda and Borel, 1991), the potential impact of climate change on floristic diversity in the Alps could be significant. Halpin (1994) states that the process is more complex than suggested above. Even if vegetation belts do not move up as a whole in response to global climate change, the ecological potential of sites will change in relation to shifts in climatic features.

The impact of climatic change on altitudinal distribution of vegetation cannot be analyzed without taking into account interference with latitudinal distribution. Especially at low altitudes, Mediterranean tree species can substitute for sub-montane belt species. In the southern French Alps, if a warming and

Box 5-5. Climate Change Impacts on Vegetation in the Scandinavian Mountains

A simple correlative and qualitative model (Holten and Carey, 1992; Holten, 1995) based on important controlling factors for plant distribution indicates that six continental eutrophic mountain plant species may come under direct threat of extinction in a "Step 2" of climate change impacts on the Fennoscandian range. "Step 2" represents the long-term (several centuries) consequences when climate exceeds the Holocene thermal optimum, resulting in both qualitative and quantitative changes in vegetation. Another 11 species regarded as potentially vulnerable may experience substantial reduction and fragmentation of their populations. The most threatened species are characterized by rarity, low competitive ability, narrow habitat amplitude, and a distributional optimum in the middle alpine zone. Increased drought and overheating will probably have the most negative short-term (50–150 years) effects on mountain plant populations. In the long term (after several centuries), if the boreal forest invades parts of the low-alpine zone, many mountain plant species will be vulnerable to extinction because of their lower competitive ability relative to boreal plants.

a decrease in precipitation were to occur, Ozenda and Borel (1991) predict a northward progression of Mediterranean ecotypes ("steppization" of ecosystems). Kienast *et al.* (1995) predict steppization on no more than 5% of today's forested areas in Switzerland. On the Italian slopes of the Alps, the northward progression of Mediterranean influences would probably be more important. A similar (xeric) change is less likely to take place in the southeastern part of the range (Julian and Carnic Alps), where a much more humid climate exists.

5.2.3.4. *Modeling of Communities and Ecosystems Responses*

There are a number of ecosystem models currently available that can be used to test the sensitivity of a particular system to processes such as nutrient cycling (e.g., CENTURY, TEM), investigate species composition under changed environmental conditions (e.g., BIOME, DOLY, MAPSS), or assess forest health (e.g., FORET).

A number of modeling studies that were based on forest gap models (Shugart, 1984) have been conducted to assess the impacts of climatic change on forest biomass and species composition in mountainous regions (e.g., Kienast, 1991; Kräuchi and Kienast, 1993; Bugmann, 1994; Bugmann and Fischlin, 1994; Kräuchi, 1994). Although several different models and climate scenarios were used in these studies, they yielded quite similar conclusions regarding the sensitivity of forests in the European Alps. As an example of such a model application, Figure 5-2 illustrates the modeled forest changes in the alpine zone under differing climatic scenarios. Potential regional development of forest vegetation (using the FORSUM model; Kräuchi, 1994) at the Derborence site in the Swiss Alps is illustrated for no change in climate (upper) and for the IPCC IS92A scenario (lower). The forest at this location is currently changing as a result of successional processes. While the overall forest biomass might remain the same, the species composition will be different under the two climates, with a reduction in the competitive dominance of *Picea abies* and an increase in the proportion of broadleaves under the IS92A scenario (Kräuchi, 1994).

Model studies for Australian mountain vegetation show that there is the potential for the expansion of woody vegetation, both trees and shrubs, in response to rising temperature (Grabherr *et al.*, 1994; Williams and Costin, 1994). The treeline may rise by 100 m for each degree increase in mean annual temperature (Galloway, 1989). Elevated summer temperatures may also lead to an expansion of shrub communities (Williams, 1990).

VEMAP (1985), a continental-scale vegetation response study of the United States, considered how three biogeographical models (BIOME2, DOLY, MAPSS; Woodward *et al.*, 1995) respond to doubled-CO_2 climate scenarios. Results on a coarse (0.5° latitude/longitude) grid showed alpine and subalpine regions in the western United States retreating to higher elevation and decreasing in area, while the subalpine montane forest boundary shifted upward. Two models also projected upward shifts in the lower montane boundary, while one produced a lowering of this boundary.

It should be emphasized that there are considerable limitations in present-day simulation techniques for assessing ecosystem response to climate change, in particular the temporal changes of these responses. In general, increases in atmospheric temperature will affect the structure and function of vegetation, as well as species composition where time may not be sufficient to allow species to migrate to suitable habitats (Kienast, 1991; Bugman, 1994; Klötzli, 1994).

5.2.4. *Impacts on Human/Socioeconomic Systems*

Because of the diversity of mountain economies, from exclusively tourist-based ones to those characterized by centuries-old subsistence agriculture, no single impact study will adequately represent the range of potential socioeconomic responses to climate change. A case-by-case approach is therefore essential to understand how, for example, mountain agriculture may change in Bolivia, tourism may change in Switzerland, or hydropower resources may be affected in New Zealand.

Because humans have influenced mountain ecosystems in many different ways throughout history, anthropogenic impacts generally cannot be dissociated from climate change impacts. Climatic influences are often obscured by the impact of change in land use. An example is the fragmentation of the forest and natural vegetation cover. Because of persistent anthropogenic influences in the past, timberline in mountains such as the Alps has dropped 150–400 m compared to its uppermost position during the postglacial optimum (Holtmeier, 1994). At present, the climatic limit of tree growth in the Alps is situated above the actual forest limit (Thinon, 1992; Tessier *et al.*, 1993). By reducing species diversity and even intraspecies genetic variability of some species, humans have reduced the ability of alpine vegetation to respond to climate change (David, 1993; Peterson, 1994).

5.2.4.1. Mountain Agriculture

Mountains contribute a substantial proportion of the world’ agricultural production in terms of economic value. Uplan regions are characterized by altitudinal climatic gradients tha can lead to rapid changes in agricultural potential over comparatively short horizontal distances. Where elevations ar high enough, a level eventually will be reached where agricultural production ceases to be profitable or where production losses become unacceptably high. Upland crop production, practiced close to the margins of viable production, ca be highly sensitive to variations in climate. The nature of tha

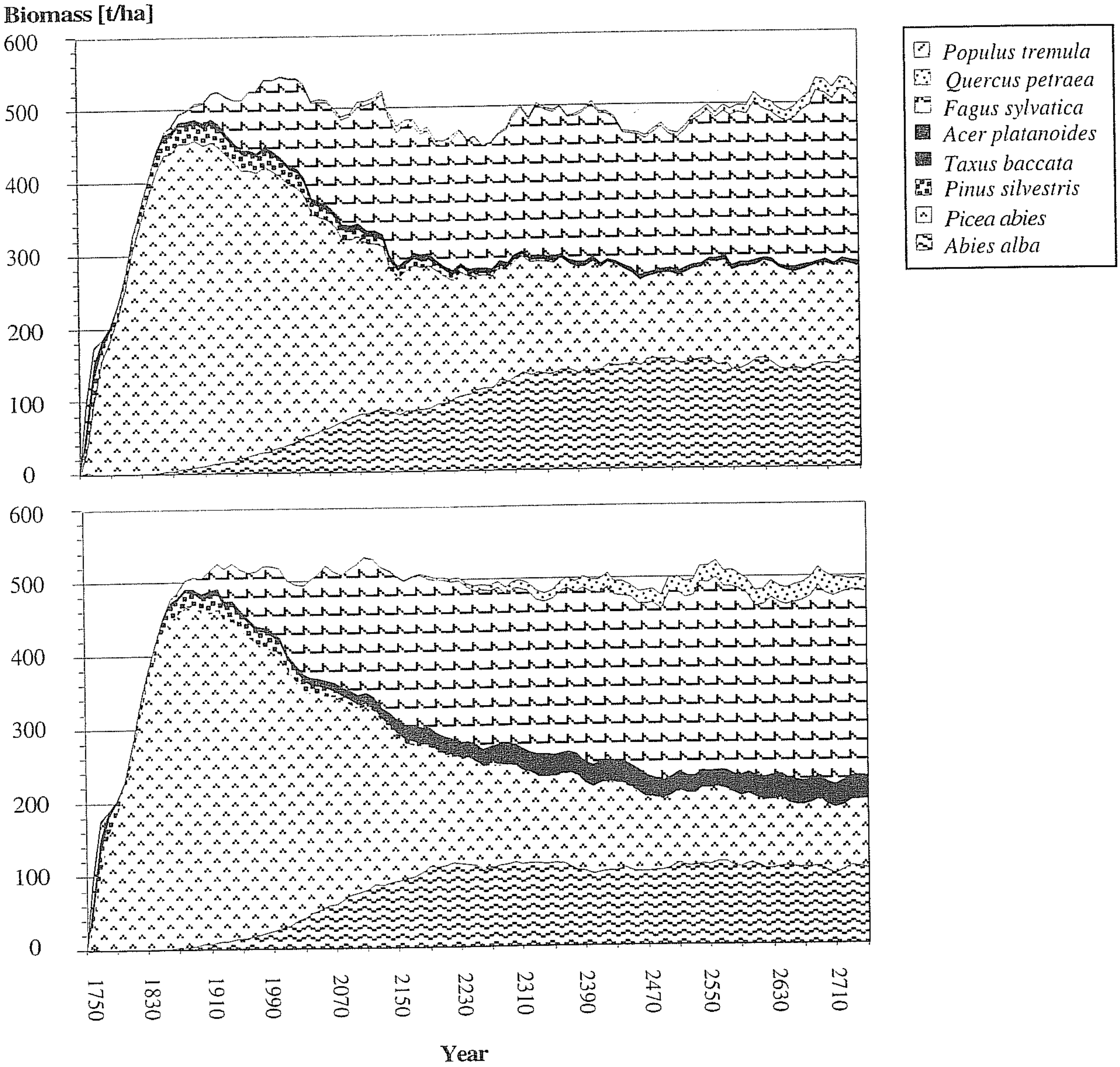

Figure 5-2: Example of simulations of forest response to different climate change scenarios in the alpine zone. Simulated forest successio on a subalpine site (mean annual temperature: 6°C; mean annual precipitation: 1,200 mm; subsoil: limestone and some flysch intersections assuming today’s climatic pattern (upper) and the IPCC IS92a climate scenario (lower; ΔT: +1°C in 2025; ΔT: +3°C in 2100) using FORSU a JABOWA/FORET-type gap model (Kräuchi, 1994). The main difference in the transient response in species composition between the baseline climate and the IS92a climate is the reduced importance of *Picea abies* combined with an increasing percentage of deciduous tree The establishment of *Quercus petraea* and *Acerplatanoides* is particularly stimulated. The site might undergo a transition from *Piceo-Abietion (Adenostylo-Abietetum* or *Equiseto-Abietetum)* to *Abieti-Fagetum*.

Box 5-6. Impacts of Climate Change on Agriculture in Upland Regions of China and Japan

Climatic warming will in general increase agricultural productivity in China (Gao *et al.*, 1993). Under the present climate, crops such as maize and rice suffer from low temperature and frost in northeast and southwest mountainous regions (Ma and Liang, 1990; Li *et al.*, 1993). The yield for crops in these areas is expected to rise with increasing temperatures (Hulme *et al.*, 1992). According to a study by Li *et al.* (1993), a mean warming of 0.4–1.0°C in the mountain regions of southwest China will move the upper boundary for growing grain by 80–170 m, and the growing areas will expand. However, there is uncertainty related to expansion of growing areas because soils are very important limiting factors for grain production. Specific soil properties include physical and chemical conditions that control plant growth, such as permeability, water holding capacity, acidity, soil structure, and density. In addition, the specific varieties that are presently used in mountain agriculture may need to be altered in order to keep up with global warming and thus present an additional economic hardship to the system.

To examine the effect of climatic variability on rice suitability, simple empirical indices have been developed relating rice yield to July/August mean air temperature in upland regions of Tohoku and Hokkaido in northern Japan (Yoshino *et al.*, 1988). In combination with information about regional lapse rates of temperature, estimates have been made of the effects of anomalous weather on yield and on potentially cultivable areas for both cool and warm departures from a current mean climate. The results indicate that a July/August temperature departure of -1.1°C in Hokkaido would reduce yields by some 25% relative to the average, and the potentially cultivable area would contract to elevations below 100 m in a small area of southwestern Hokkaido, where the Sea of Japan acts to ameliorate the climate. A comparable anomaly in Tohoku (-1.0°C) would produce a 13% yield shortfall, and the cultivable area would contract by some 20%, to areas below about 200 m.

Conversely, in warmer-than-average years, higher yields would occur in association with an upward shift in limits of potential cultivation (Carter and Parry, 1994). A temperature rise of more than 3°C would also lead to a yield increase, but while current varieties of rice tend to respond positively to small temperature increments, they are less well adapted to large departures. It is likely that later-maturing varieties would be adopted under much warmer conditions to exploit the greater warmth. Under this scenario, most of the land below 500 m could become viable in Hokkaido, as could land up to 600 m in Tohoku.

sensitivity varies according to the region, crop, and agricultural system of interest. In some cases, the limits to crop cultivation appear to be closely related to levels of economic return. Yield variability often increases at higher elevation, so climate change may mean a greater risk of yield shortfall, rather than a change in mean yield (Carter and Parry, 1994).

Several authors have predicted that currently viable areas of crop production will change as a result of climate change (Alps: Balteanu *et al.*, 1987; Japan: Yoshino *et al.*, 1988; New Zealand: Salinger *et al.*, 1989; and Kenya: Downing, 1992), although other constraints such as soil types may make agriculture unsuitable at these higher elevations. In-depth studies of the effects of climatic change in Ecuador's Central Sierra (Parry, 1978; Bravo *et al.*, 1988) and Papua New Guinea (Allen *et al.*, 1989) have shown that crop growth and yield are controlled by complex interactions among different climatic factors and that specific methods of cultivation may permit crop survival in sites where the microclimates would otherwise be unsuitable. Such specific details cannot be included in GCM-based impact assessments, which have suggested both positive and negative impacts—such as decreasing frost risks in the Mexican highlands (Liverman and O'Brien, 1991) and less productive upland agriculture in Asian mountains, where impacts would depend on various factors, particularly types of cultivars and the availability of irrigation (Parry *et al.*, 1992).

Given the wide range of microclimates already existing in mountain areas that have been exploited through cultivation of diverse crops, direct negative effects of climate change on crop yields may not be too great. While crop yields may rise if moisture is not limiting, increases in the number of extreme events may offset any potential benefits. In addition, increases in both crop and animal yields may be negated by greater populations of pests and disease-causing organisms, many of which have distributions that are climatically controlled.

More important in certain parts of the developing world is the potential for complete disruption of the life pattern of mountain villages that climate change may represent in terms of food production and water management. People in the more remote regions of the Himalayas or Andes have for centuries managed to strike a delicate balance with fragile mountain environments; this balance would likely be disrupted by climate change, and it would take a long time for a new equilibrium to be established. In cases such as this, positive impacts of climate change (e.g., increased agricultural production and/or increased potential of water resources) are unlikely because the combined stressors, including negative effects of tourism, would overwhelm any adaptation capacity of the environment.

Compounded with these effects are those related to augmented duration and/or intensity of precipitation, which would enhance soil degradation (erosion, leaching, and so forth) and lead to loss of agricultural productivity.

5.2.4.2. *Hydropower*

An important socioeconomic consequence of global warming on the hydrological cycle is linked to potential changes in runoff extremes. Not only the mountain population but also the people in the plains downstream (a large proportion of the world population) presently depend on unregulated river systems and thus are particularly vulnerable to climate-driven hydrological change. Current difficulties in implementing water resource development projects will be compounded by uncertainties related to hydrologic responses to possible climate change. Among these, possible increases in sediment loading would perturb the functioning of power-generating infrastructure.

Sensitivity of mountain hydrology to climate change is a key factor that needs to be considered when planning hydropower infrastructure. In the future, a warmer and perhaps wetter greenhouse climate needs to be considered. The impact of climate on water resources in alpine areas has previously been examined by Gleick (1986, 1987a, 1987b) and Martinec and Rango (1989). Similar studies have related electricity demand to climate (Warren and LeDuc, 1981; Leffler *et al.*, 1985; Maunder, 1986; Downton *et al.*, 1988). However, few have attempted to integrate these impacts of climate change by considering both electricity supply and electricity consumption (Jäger, 1983).

Mountain runoff (electricity supply) and electricity consumption (demand) are both sensitive to changes in precipitation and temperature. Long-term changes in future climate will have a significant impact on the seasonal distribution of snow storage, runoff from hydroelectric catchments, and aggregated electricity consumption. On the basis of a study made in the Southern Alps of New Zealand, Garr and Fitzharris (1994) conclude that according to future climate scenarios (New Zealand Ministry for the Environment, 1990), the seasonal variation of electricity consumption will be less pronounced than at present—with the largest changes in winter, which corresponds to the time of peak heating requirements. There will also be less seasonal variation in runoff and more opportunity to generate power from existing hydroelectric stations. The electricity system will be less vulnerable to climate variability, in that water supply will increase but demand will be reduced. These conclusions suggest that climate change will have important implications for hydroelectricity systems in other mountain areas as well.

5.2.4.3. *Commercial Activities: Timber and Mining*

Commercial utilization of mountain forests can be affected directly and indirectly by climate change. Direct effects include loss of viability of commercial species, including problems in regeneration and lower seedling survival. Indirect effects relate to disturbances such as fire, insect, and disease losses. These indirect effects depend on the influence of climate on the disturbance agents themselves, as discussed more fully in Chapter 1.

Many of the commercially viable mineral deposits in the world are located in mountain regions. While climate has only a minor direct influence on exploitation of these resources, it may exert a significant indirect influence. Mining causes a surface disruption and requires roads and other infrastructure. Changes in climate that lead to increases in precipitation frequency and/or intensity exacerbate the potential for mass wasting and erosion associated with these developments. Furthermore, the economics of mineral expolitation often requires *in situ* processing of the extracted ore—for example, smeltering and hydrochemical processing. In the latter case, climate, especially precipitation and temperature, is a critical factor in process design.

5.2.4.4. *Tourism*

Resources required for tourism are climate-dependent—that is, their availability may be affected in the short and long term by variability, extremes, and shifts in climatic means. These resources include the landscapes of natural and anthropogenically influenced ecosystems and climatic conditions that are suitable for specific activities (Price, 1994).

Impacts of climate change on tourism in mountain areas may be divided into two types: direct and indirect. The former would result from changes in the atmospheric resources necessary for specific activities (e.g., clean air, snow). Indirect changes may result from these changes and from wider-scale socioeconomic changes, for example, fuel prices and patterns of demand for specific activities or destinations. Various indirect impacts may also derive from changes in mountain landscapes—the "capital" of tourism (Krippendorf, 1984)—which might lead potential tourists to perceive them as less attractive, and consequently to seek out new locations. There also may be new competition from other tourist locations as climates change, particularly on seasonal timeframes, especially in relation to vacation periods.

5.2.4.4.1. *Winter tourism*

Scenarios derived from GCMs have been used to examine the possible implications of climate change for skiing in Australia (Galloway, 1988; Hewitt, 1994; Whetton, 1994), Austria (Breiling and Charamza, 1994), eastern Canada (McBoyle and Wall, 1987; Lamothe and Périard, 1988), and Switzerland (Abegg and Froesch, 1994). These studies show that, because the length of the skiing season is sensitive to quite small climatic changes, there could be considerable socioeconomic disruption in communities that have invested heavily in the skiing industry. To some extent, such impacts might be offset by new opportunities in the summer season and also by investment in new technologies, such as snow-making equipment, as long as climatic conditions remain within appropriate bounds. Such investments, following seasons with little snow, have provided some "insurance" in mountain regions of North America. Investment in snow-making equipment has been somewhat less widespread in some European countries such as Switzerland (Broggi and Willi, 1989), despite the fact that seasons with little snow, especially at critical times such as during the Christmas and New Year period, can be economically devastating to mountain communities. Artificial snow-making often raises environmental concern because of the quantities of energy and water required for snow-making, the disturbances generated during the operation of the equipment, and the damage to vegetation observed following the melting of the artificial snow cover.

5.2.4.4.2. Mountain-protected areas

Types of tourism vary from "wilderness tourism" in relatively pristine ecosystems to highly developed resorts designed initially for downhill skiing and, increasingly, for year-round use. The question of the management of protected areas in North American mountains under global climate change has been considered by Peine and Martinka (1992), Peterson *et al.* (1990), and Peine and Fox (1995). These studies predict increasing conflicts between different objectives, particularly recreational use and the protection of ecosystems and species.

Strategies advanced for mitigating adverse effects of global climate change include the establishment of refugia (i.e., areas protected by law from human influences). Mountain-protected areas represent a topographically complex environment that is important for the economic and spiritual sustenance of many human cultures. As human populations continue to grow, use of this biologically diverse resource has accelerated, highlighting a strategic role for protected areas that includes both conservation and scientific interests. From a global conservation perspective, protecting representative samples of mountain resources is a high-priority goal. At the same time, scientists are more frequently using protected areas as controls for land-use research and as sites for long-term environmental monitoring. Despite their environmental and scientific value, however, such preserves represent small and fragmented landscapes, making them vulnerable to species migrations and extinctions.

5.3. Future Research and Monitoring Needs

Future research needed to understand and predict effects of climatic change on mountain regions should represent balance and coordination between field studies, including paleoenvironmental data collection; monitoring; experimental studies; and modeling (Guisan *et al.*, 1995). Research requirements include:

- Specific regional field studies (transects, data acquisition, mapping, observations at high elevation, and so on).
- Paleo data to establish baselines, to evaluate responses of ecosystems to natural climate variability, and to provide data for model verification
- Monitoring to establish long-term baseline data, in particular in potentially sensitive regions (e.g., remote areas, high elevations)
- Experimental studies to improve fundamental understanding, to test hypotheses, and to provide empirical information for modeling studies
- Modeling to ameliorate climate scenarios using various downscaling approaches, to improve understanding of how topographic and edaphic variability influence ecosystems and natural resources on the regional scale, and to improve mechanistic modeling of physical, biological, and socioeconomic systems
- Integrated assessment models to address the complex interrelationships of different systems in mountain regions and to provide valuable multidisciplinary information to a range of end-users, including policymakers.

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