The Risks Associated with Climatic Change in Mountain Regions

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Keywords: Biodiversity, Climatic change, Climate modeling, Extreme events, Risk, Water resources.

1. Introduction

The Earth's environment is continuously subjected to various stresses through natural processes and human interference. With the rapid industrialization and population growth that the 20th century has experienced worldwide, however, humankind has added a new dimension of stress to the global environment in general, and mountain regions in particular. In some instances, environmental degradation is inevitable because of the basic requirements of human populations, particularly where those are growing rapidly; in other cases, environmental damage is a direct result of mismanagement and over-exploitation of natural resources (Beniston 2000). The sensitivity of a given mountain region to changes in environmental conditions depends largely upon the climatic, geological and biological features of the region considered. Changes in these controlling factors, particularly through direct human interference or indirect effects such as climatic change, may have significant impacts upon numerous mountain environments.

2. Modeling changes in climate and climatic extremes in mountain regions

The current spatial resolution of General Circulation Models (GCM) is generally

U. M. Huber et al. (eds.), Global Change and Mountain Regions, 511-519.

too crude to adequately represent the orographic detail of most mountain regions and therefore the complexities of regional climates. On the other hand, most climatic impacts research requires information at fine spatial definition, where the regional details of topography or land-cover are important determinants in the response of natural and managed systems to change. Since the mid-1990s, the scaling problem related to complex orography has been addressed through regional modeling techniques, pioneered by Giorgi and Mearns (1991), and through statistical-dynamical downscaling techniques (e.g. Zorita and von Storch, 1999).

In this context, it is recognized that many natural and managed systems are far more sensitive to climatic extremes than to changes in mean climate. In the Alps, a warmer and perhaps more extreme climate is likely to result in increasingly frequent hazards, related to the reduction of slope stability (e.g. through permafrost degradation and loss of vegetation cover following shifts in ecosystem distribution). An increase in the frequency of intense precipitation events will enhance the severity of natural hazards, such as floods, slope erosion, and avalanches. Research on the impacts of extreme climatic events thus needs to focus on cryospheric, hydrologic and biospheric issues both at high elevations, where the sensitivity of natural systems to change is high (e.g. Keller et al. 2000), and at lower elevations. Extreme climatic events are often accompanied by significant losses resulting from damage to infrastructure and to forests and crops (as witnessed during the storms of end-December 1999 where the total costs across Europe exceeded US$20 billion). Hence, the quantification of future trends in weather extremes in a changing global climate, and their translation into economic losses, are of long-term strategic interest to mountain countries such as Switzerland.

In the context of a Swiss network research program (NCCR-Climate), the Department of Geography of the University of Fribourg is currently investigating extreme climate events such as wind-storms, high precipitation, and the persistence of heat or drought (Goyette et al. 2001; 2003; Jungo et al. 2002). Modeling climatic extremes addresses more than a simple set of simulations in which the differences in temperature and precipitation between a particular baseline and some point in the future are quantified. At the spatial scales relevant to mountain environments, there are numerous interactive systems that need to be taken into account, in particular land-use patterns, snow and ice, water resources, and ecosystems. Decadal-scale variability of the climate system that can modulate the intensity and frequency of certain extremes also need to be considered when attempting to simulate shifts in extreme events. For example, changes in the extremes of temperature and moisture in the Alpine region can be particularly sensitive to the behavior of the North Atlantic Oscillation, as shown by Jungo and Beniston (2001) and Beniston and Jungo (2002).

In order to understand the fundamental mechanisms underlying regional extremes in wind and temperature, their variability and persistence, and their shifts in a changing global climate in the 21st century, investigations at the University of Fribourg make use of the Canadian Regional Climate Model CRCM-2 (e.g. Laprise et al. 1998). The numerical modeling of climatic processes at the regional scale enables the identification of causal mechanisms and, in addition, allows a certain degree of predictability. The regional climate model (RCM) procedures currently applied to the simulation of wind storms over Western Europe and their impacts on the Alps involve a numerical "cascade" process, by which the model successively increases its spatial definition (resolution) in order to focus upon regions where there may be high sensitivity of infrastructure, forests, and slope stability. In the work by Goyette et al. (2001), for example, a low-resolution (60 km grid mesh) captures the essence of the synoptic weather systems that generate local or regional extremes, and then "feeds" a 5-km version of the model to ameliorate the quality of regional-scale simulations. Finally, in order to reproduce and document areas particularly affected by wind damage, or related to extended heat and drought stress, a 1-km resolution is applied to the region of interest. Figure 1 illustrates the CRCM-2 cascade process, zooming in progressively from the Europe-Atlantic scale to the scale of a large mountain valley.

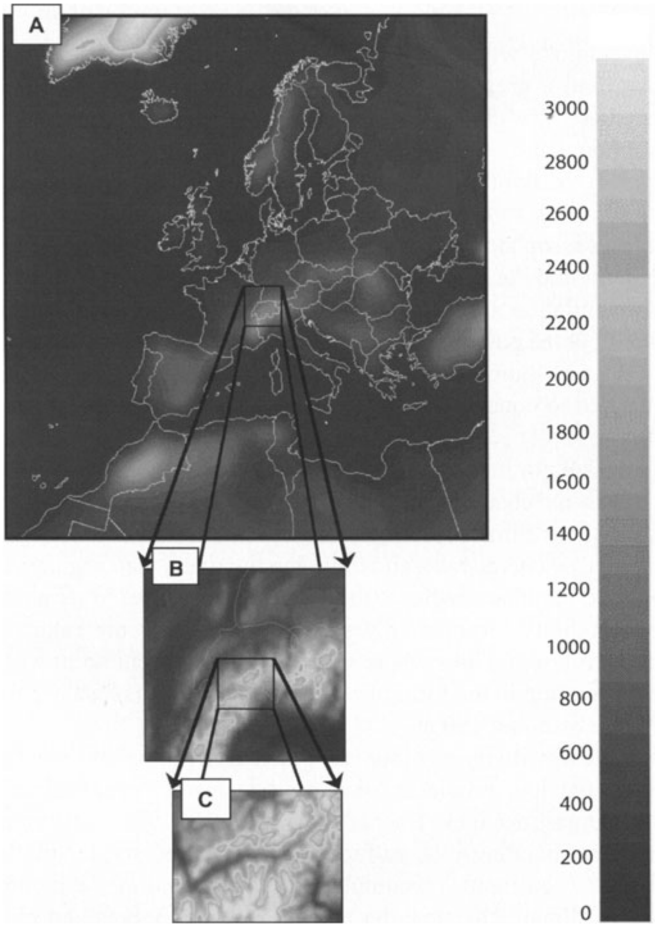

Figure 1: Illustration of the regional climate model "self-nesting" scheme that allows the investigation of climatic processes at increasingly finer scales (after Goyette et al. 2001). Domain A uses a 60-km grid, domain B a 5-km grid, and domain C a 1-km grid. This latter resolution enables the impacts of severe climatic events to be quantified. The legend on the right is terrain height in meters.

In such types of climatic change investigations, risk analysis is a necessary part of the approach, because it is necessary to quantify potential increases in damage in order to prepare for adequate response strategies by stakeholders, essentially local authorities. Risk and cost-benefit analyses help to determine whether the probable increases in damage costs warrant investments for protection infrastructure or other measures. On the basis of regional climate scenarios, and a quantification of the potential impacts on the natural environment, new strategies essentially linked to sustainability can be tracked and publicized. Such strategies should be promoted as they constitute a way of mitigating the consequences of global change on a wide range of economic, political and social sectors in mountain regions.

3. Risks associated with climatic change in mountain regions

A warming climate will enhance the hydrological cycle, implying higher rates of evaporation, and a greater proportion of liquid precipitation compared to solid precipitation; these physical mechanisms, associated with potential changes in precipitation amount and seasonality, will affect soil moisture, groundwater reserves, and the frequency of flood or drought episodes. Though water is present in ample quantity at the Earth's surface, the supply of water is limited and governed by the renewal processes associated with the global hydrological cycle. With the expansion of human settlements and the growth of industrial activities, water has been increasingly used for the assimilation and discharge of wastes. This resource has been taken for granted, and only in the past few decades has increasing water shortage and declining water quality from pollution drawn attention to the inherent fragility and scarcity of water. This has led to concerns about water availability to meet the requirements of the 21st century.

Snow and ice are, for many mountain ranges, a key component of the hydrological cycle, and the seasonal character and amount of runoff is closely linked to cryospheric processes. A changing climate is likely to lead to shifts in seasonal snow pack; glacier melt will influence discharge rates and timing in the rivers that originate in mountains. In most temperate mountain regions, the snow-pack is close to its melting point, so that it responds rapidly to apparently minor changes in temperature. As warming progresses in the future, regions where snowfall is the current norm will increasingly experience precipitation in the form of rain. For every °C increase in temperature, the snowline will rise by about 150 m.

Because of the sensitivity of mountain glaciers to temperature and precipitation, the behavior of glaciers provides some of the clearest evidence of atmospheric warming over the past decades (Haeberli and Beniston 1998). The volume of ice in a glacier, and correspondingly its surface area, thickness, and length, is determined by the balance between inputs (accumulation of snow and ice) and outputs (melting and calving). As climate changes, the balance between inputs and outputs may be altered, resulting in a change in thickness and the advance or retreat of the glacier. Temperature, precipitation, humidity, wind speed, and other factors such as slope and the reflectivity of the glacier surface all affect the balance between inputs and outputs (Fitzharris et al. 1996).

There is widespread evidence that glaciers are retreating in many mountain areas of the world. Since 1850, the glaciers of the European Alps have lost about 30 to 40% of their surface area and about half of their volume (Haeberli and Beniston, 1998). Similarly, glaciers in the Southern Alps of New Zealand have lost 25% of their area over the last 100 years, and glaciers in several regions of central Asia have been retreating since the 1950s (Fitzharris et al. 1996; Meier 1998). Glacial retreat is also prevalent in the higher elevations of the tropics. Glaciers on Mt. Kenya and Kilimanjaro have lost over 60% of their area in the last century (Hastenrath and Greischar 1997), and accelerated retreat has been reported for the tropical Andes (Thompson et al. 2000).

Empirical and energy-balance models indicate that 30 – 50% of existing mountain glacier mass could disappear by the year 2100 if global warming scenarios in the range of 2-4°C indeed occur (Fitzharris et al. 1996; Haeberli and Beniston 1998). The smaller the glacier, the faster it will respond to changes in climate. As a result, many glaciers in temperate mountain regions would lose most of their mass within decades.

Because mountains are the source region for over 50% of the globe's rivers, the impacts of climatic change on hydrology are likely to have significant repercussions not only in the mountains themselves but also in populated lowland regions that depend on mountain water resources for domestic, agricultural, energy and industrial purposes. Water resources for populated lowland regions are influenced by mountain climates and vegetation; snow feeds into the hydrological basins and acts as a control on the timing of water runoff in the spring and summer months. Hydrological systems are also controlled by soil moisture, which largely determines the distribution of ecosystems, groundwater recharge, and runoff; the latter two factors sustain river flow and can lead to floods.

Significant shifts in climatic conditions will also have an effect on social and economic systems in many regions through changes in demand, supply and water quality. In regions which are currently sensitive to water stress (arid and semi-arid mountain regions), any shortfalls in water supply will enhance competition for water use for a wide range of economic, social, and environmental applications. In the future, such competition will be sharpened as a result of larger populations, which will lead to heightened demand for irrigation and perhaps also industrialization, at the expense of drinking water (Beniston 2002).

Because of increasing population, the additional demand will be accompanied by a sharp decline in water availability per capita. A consumption of 1,000 m^3 of water per year, per capita is considered a standard for "well-being" in the industrialized world. Projections of annual water availability per capita within the next 20 years, however, show a declining trend in many parts of the world, including those that are considered to have ample water resources (Shiklomanov 2001). Figure 2 illustrates the changes that are projected between current and future water availability. This is a reflection of the combined influence of environmental change (e.g. modified precipitation patterns in a changing climate) and socio-economic trends (e.g. sustained population growth in many of these countries, implying a reduction in per capita availability even if water amounts remain the same as today). In many instances, the impact of population

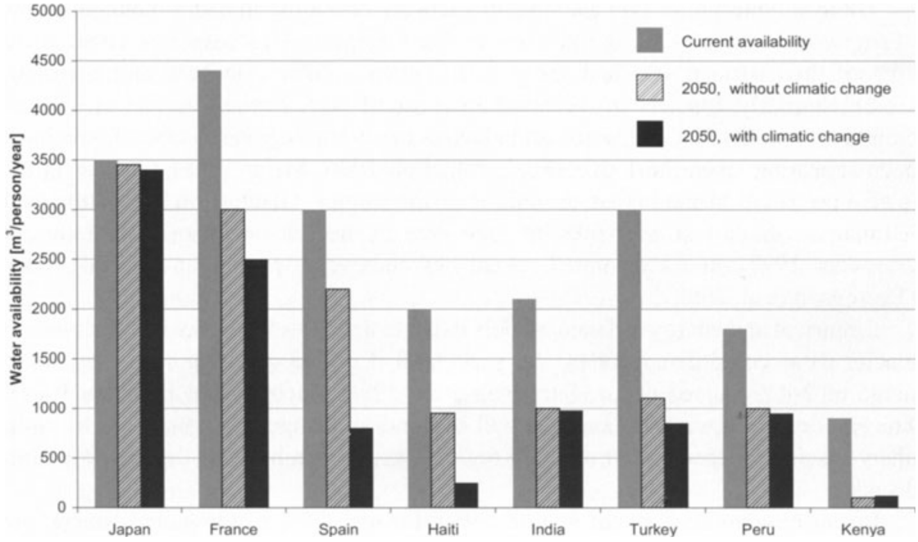

Figure 2: Water availability under current climatic conditions; in 2050 without shifts in climate; and in 2050 with climatic change (after Shiklomanov 2001).

growth may in fact be larger than that of climatic change itself, the latter being merely an exacerbating factor (IPCC 2001).

Geomorphological hazards are part of a larger group of natural hazards, including floods, soil or water quality risks due to agricultural technologies, desertification, sudden weather changes and wildfires. Climate change could alter the magnitude and/or frequency of a wide range of geomorphologic processes. Increases in extreme precipitation events, associated with snowmelt, could increase the frequency and severity of floods. In the mountain regions of Asia affected by the Monsoon, for example, loss of revenue in agriculture and damage to infrastructure related to Monsoon storms represent a high proportion of annual loss, as reported by Carver and Nakarmi (1995). Increased severity and frequency of storms during the Monsoon period in the future may lead to higher rates of erosion and more frequency of flooding in the Himalayas. Such extreme events would affect erosion, discharge and sedimentation rates. Furthermore, sediments deposited in large quantities on agricultural lands, irrigation canals and streams could lead to disruptions of agricultural production.

Erosion by rivers at the base of slopes increases slope steepness and hence the potential for increased hazards. Slow movement of landslides and gradual creep of rock and soil down-slope can be as destructive as fast slides but are less likely to cause loss of life. Debris flows, on the other hand, are rapid flows of water laden with rocks and sediments. Material on steep slopes that becomes saturated with water after prolonged intense rain or abrupt snow melt may develop a debris flow or mud flow (Dikau et al. 1997) resulting in destruction to infrastructure, forests and ecosystems. Loss of life can be high because of the unexpected and rapid nature of debris-flow events.

A further hazard leading to decreased slope stability is related to changes in the cryosphere at high elevations. The retreat of glaciers, and the corresponding changes in landscape could be one of the more immediately perceptible signals of climate change (Haeberli and Beniston 1998). Because the recolonization of vegetation on sparse and fragile mountain soils is slow, deglaciated morainic deposits can remain unprotected against erosion for decades to centuries. On slopes whose angles are steeper than 25-30°, stability problems can arise in newly exposed areas or those where permafrost thawing becomes significant. With the melting of the present permafrost zones at high mountain elevations, rock and mud-slide 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 loss of life and the damage costs to constructions are certain to 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 and areas characterized by steep slopes (e.g. suburbs of South American Andean cities, Hong Kong, or Los Angeles) have spread into high-risk areas, thus enhancing their exposure to landslide hazards.

Fire is an element that is of particular importance in many ecological systems; it is destructive in numerous circumstances, but also plays a valuable role in the recycling of organic material and the regeneration of vegetation. Changing climatic conditions are likely to modify the frequency and intensity of fire outbreaks, but there are other factors that need to be considered as well. For example, changes in fire-management practices and forest dieback in response to external stress factors can impact fuel characteristics and can lead to increased fire risk (King and Neilson 1992).

With climatic change as projected by the IPCC (2001), prolonged periods of summer drought would transform areas already sensitive to fire into regions of sustained fire hazard. The coastal ranges of California, the Blue Mountains of New South Wales (Australia), Mt. Kenya, and mountains on the fringes of the Mediterranean Sea, already subject to frequent fire episodes, would be severely affected. In addition, many of these regions are located close to major population centers, and thus considerable damage to infrastructure and disturbances to economic activities at the boundaries of many large urban areas might be expected. Cities such as Los Angeles and the San Francisco Bay Area in California, Sydney in Australia, coastal resorts close to the mountains in Spain, Italy, and southern France could become more vulnerable in the future as fire hazards increase in response to climatic change and urban centers expand in response to population pressures. Fires could also break out in regions that are currently relatively unaffected, as critical climatic, environmental and biological thresholds for fire outbreaks are exceeded (e.g. Johnson 1992).

4. Conclusions

Mountains are unique features of the Earth system in terms of their scenery, their climates, their ecosystems; they provide key resources for human activities well beyond their natural boundaries; and they harbor extremely diverse cultures in both the developing and the industrialized world. The protection of mountain environments against the adverse effects of economic development should be a priority for both today's generation and the generations to come (Beniston 2000).

In facing up to environmental change, human beings are going to have to think in terms of decades and centuries. Many of the impacts of these profound changes may not become unambiguously apparent for several generations. Many of the policies and decisions related to pollution abatement, climatic change, deforestation or desertification would provide opportunities and challenges for the private and public sectors. A carefully selected set of national and international responses aimed at mitigation, adaptation and improvement of knowledge can reduce the risks posed by environmental change to water resources and natural hazards.

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