CLIMATE VARIABILITY AND CHANGE IN HIGH ELEVATION REGIONS: PAST, PRESENT AND FUTURE

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Abstract. This special issue of *Climatic Change* contains a series of research and review articles, arising from papers that were presented and discussed at a workshop held in Davos, Switzerland on 25–28 June 2001. The workshop was titled 'Climate Change at High Elevation Sites: Emerging Impacts', and was convened to reprise an earlier conference on the same subject that was held in Wengen, Switzerland in 1995 (Diaz et al., 1997). The Davos meeting had as its main goals, a discussion of the following key issues: (1) reviewing recent climatic trends in high elevation regions of the world, (2) assessing the reliability of various biological indicators as indicators of climatic change, and (3) assessing whether physical impacts of climatic change in high elevation areas are becoming evident, and to discuss a range of monitoring strategies needed to observe and to understand the nature of any changes.

1. Why the Focus on Mountains?

The world's mountain systems, including the people in them, have gained an international focus during the last few decades. In many respects, the United Nations' International Year of Mountains–2002 is the culmination of a long process involving research, development of research networks, a greater awareness by various sectors of society of the critical importance of mountain regions for a sustainable future, and recognition of that fact by policy makers.

Past efforts and accomplishments in this area include the U.N.'s Environmental Scientific and Cultural Organization's (UNESCO) Man and the Biosphere (MAB-6) programme beginning in 1971, the successive worldwide establishment of regional multinational research institutions and cross-border research and information networks, the recognition of 'Mountains' in the political Agenda 21 of the U.N. Conference on Environment and Development (UNCED) 1992 in Rio de Janeiro, Brazil (Chapter 13), and the follow-up Earth Summits known as Rio+5 and Rio+10, finally leading to the start of the Mountain Research Initiative (MRI) in 2001 (Becker and Bugmann, 2001). The MRI is an international collaborative research effort that involves the International Geosphere-Biosphere Programme (IGBP), the Global Terrestrial Observing System (GTOS) and the International Hu-

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man Dimensions of Global Change programme (IHDP) – a truly interdisciplinary approach.

Mountains cover 25% of the global land surface, providing home and living space for 26% of the world's population. In arid and semi-arid areas, where water is critical, mountains provide as much as 90–100% of the freshwater resources for drinking, irrigation, and industrial supply in the surrounding lowlands (Meybeck et al., 2001). Mountains have also been shown to be hotspots of biodiversity – reason enough for the world's nations to establish a firm commitment to help sustain mountain environments in the future (NRC, 1999).

2. Climatic Changes and Mountains

Mountains are unique ecosystems covering all latitudinal belts and encompassing within them all the earth's climatic zones. Mountains are widely recognized as containing highly diverse and rich ecosystems, and thus, they are key elements of the global geosphere-biosphere system. At the same time, mountains contain ecosystems that are quite sensitive and highly vulnerable to natural risks, disasters, and ecosystem changes, be it through the occurrence of rapid mass movements, such as landslides, or via slow land degradation due to human activities, with all the attendant socioeconomic consequences (Messerli and Ives, 1997).

Many studies (e.g., Thompson, 2000) suggest that high elevation environments, comprising glaciers, snow, permafrost, water, and the uppermost limits of vegetation and other complex life forms are among the most sensitive to climatic changes occurring on a global scale. The stratified, elevationally-controlled vegetation belts found on mountain slopes represents an analogue to the different latitudinally-controlled climatic zones, but these condensed vertical gradients are capable of producing unique hotspots of biodiversity, such as those that serve as habitat for a variety of species ranging from butterflies, frogs and toads, to species of birds, trout and salmon. High relief and high gradients make mountain ecosystems very vulnerable to slight changes of temperatures and to extreme precipitation events.

Likewise, mountains provide life-sustaining water for most regions of the world. The critical function of mountains as seasonal and longer-term water storage implies that climatic and other environmental changes in the world's mountains will have a large impact, not only on those immediate regions, but for a much greater area as well. In essence, mountain regions provide a discreet quantifiable domain where relatively small perturbations in global processes, can cascade down to produce large changes in most or all of the myriad interdependent mountain systems, from its hydrological cycle to its complex fauna and flora, and the people that depend on those resources.

What will changes in global climate mean at the regional scale? Are mountains intrinsically more sensitive than other ecosystems? How big of a threat to the future of mountain regions is global climate change? Are we monitoring the right variables? Are the relevant observing systems adequate to the task? Can we identify critical systems at risk (i.e., 'canaries in the coal mine') that will alert us to imminent and perhaps irreversible changes impacting montane systems?

We do not yet have the answers to these questions. But, in this volume, we see evidence that investigations of mountain ecosystems may provide critical insights into understanding climate variability and its impacts. A particular and unique feature of mountain ecosystems is the steep temperature gradients due to the complex topography. Changes in temperature, together with humidity, and in the occurrence of extreme climatic events, are some of the key impacts expected under global climate change. Temperature and humidity changes imply changes in sensible and latent heat fluxes, which are modulated by the atmospheric circulation on different space and time scales, and which in turn control many biogeochemical processes, including non-linear effects, thresholds, and phase-transitions. Examples are growth limits for plants near the timberline or at the upper limit of the alpine life zones. Temperature also controls the volatility of many toxic substances (e.g., volatile organic compounds, mercury). Studies have shown that cold high mountain regions are preferred areas for atmospheric scavenging and deposition.

Among the most important thresholds of the global ecosystem is the phase transition of the water molecule from its liquid to the solid state around 0 °C. Particularly in mid- and low-latitude areas of the globe, this threshold plays a strong role in mountain areas, be it at daily scales (e.g., frost cycles) or at multi-annual to decadal or centennial scales (e.g., permafrost and glaciers). In the frozen form of snow and ice, water is naturally stored in mountains and buffers seasonal and interannual water shortage due to climate variability. For example, although the Alps cover only 23% of the Rhine River catchment, in the dry summer of 1976, snow and ice melt from the mountains contributed as much as 95% of the total Rhine discharge into the North Sea. Small temperature changes around the 0 °C threshold strongly modulate the amount and timing of runoff and peak discharge in rivers and thus control floods. Water, snow, ice, and freeze-thaw cycles are prominent weathering agents, account for a wide range of natural hazards, and are a key component for a number of socio-economic activities, including tourism and energy production.

These are some of the reasons why we focus on climatic changes in mountain regions in the present volume, particularly on changes in temperature, the water cycle, the cryosphere, and on selected ecosystem responses in some mountain areas. We fully recognize that there are many other equally important scientific issues related to mountain research, and it is not our intent here to be all-inclusive. More comprehensive reviews have appeared in the literature (IPCC, 1996; Messerli and Ives, 1997), although in the more recent IPCC assessment reports (e.g., IPCC, 2001) the subject of changes induced by global climate change in mountain environments is not developed explicitly, and instead must be found in other contexts. However, the subject matter is extremely important for a variety of reasons (see, e.g., Schimel et al., 2002), and the present volume addresses some of the key issues regarding climatic change in high elevation regions.

Mountain research requires a truly inter- and multidisciplinary approach that includes the natural, social, health, and engineering sciences (Messerli and Bernbaum, 2002). Within that framework, our goal as organizers of the Davos workshop, is to present new information about recent trends and impacts of climate variability and climate change in mountain regions. The articles in this special issue address findings from observations applicable on multiple time and spatial scales, as well as from modeling work; they deal with some of the more important elements in mountain research, and particularly with issues related to global climate change. As noted above, this issue occupies an important place in national and international scientific activities because of its wide-ranging impacts on biogeophysical and socio-economic systems. This volume may be viewed as one contribution towards the goal of future sustainability of our mountain regions.

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