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SENSITITVITY OF MOUNTAIN REGIONS TO CLIMATIC CHANGE

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Introduction

Mountain systems cover about one-fifth of the earth's continental areas and are all inhabited to a greater or lesser extent except for Antarctica. Mountains provide direct life support for close to 10% of the world's population, and indirectly to over half. Because of their great altitudinal range, mountains such as the Himalayas, the Rockies, the Andes, and the Alps, exhibit, within short horizontal distances, climatic regimes which are similar to those of widely separated latitudinal belts; they consequently feature high biodiversity. Indeed, there is such a close link between mountain vegetation and climate that vegetation belt typology has been extensively used to define climatic zones and their altitudinal and latitudinal transitions (cf. for example Klötzli, 1984, 1991, 1994; Ozenda, 1985; Quezel and Barbero, 1990; Rameau et al., 1993).

Mountains are also a key element of the hydrological cycle, being the source of many of the world's major river systems. Shifts in climatic regimes, particularly precipitation, in space or seasonally in a changing global climate, would impact heavily on the river systems originating in mountain areas, leading to disruptions of the existing socio-economic structures of populations living within the mountains and those living downstream.

Although mountains may appear to be mere roughness elements on the earth's surface, they are in fact an important element of the climate system. They are one of the trigger mechanisms of cyclogenesis in mid latitudes, through their perturbations of large-scale atmospheric flow patterns. The effects of large-scale orography on the atmospheric circulation and climate in general have been the focus of numerous investigations, such as those of Bolin (1950), Kutzbach (1967), Manabe and Terpstra (1974), Smith (1979), Held (1983), Jacqmin and Lindzen (1985), Nigam et al. (1988), Broccoli and Manabe (1992) and others. One general conclusion from these comprehensive studies is that orography, in addition to thermal land-sea contrasts, is the main shaping factor of the stationary planetary waves of the winter troposphere in particular. The seasonal blocking episodes experienced in many regions of the world, with large associated anomalies in temperature and precipitation, are closely linked to the presence of mountains.

A precise understanding of the climatic characteristics of mountain regions is complicated on the one hand by a lack of observational data at the spatial and temporal resolution adequate for climate research in regions of complex topography, and on the other by the considerable difficulty in representing complex terrain in current general circulation climate models (GCMs). Mountains are important perturbation factors to large-scale atmospheric flows; they also have an influence on the formation of clouds and precipitation in their vicinity, which are in turn indirect mechanisms of heat and moisture transfer in the vertical. Consequently, the influence of orography on climate needs to be taken into account in a physically-meaningful manner. Parametric schemes in GCMs take a number of possible forms, such as "envelope topography" which smoothes the real orography over continental areas. Large-scale orographic forcing is then derived by filtering the orography at smaller scales and effects of the atmospheric boundary layer. Gravity waves generated by the presence of the underlying orography on the atmosphere are capable of breaking in a similar manner to ocean waves at the seashore, and in doing so transfer substantial quantities of momentum from the large-scale to the small-scale flows.

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 the specificities of climate within the mountain environments themselves. These include microclimatological processes which feed into the large-scale flows, and the feedbacks between the surface and the atmosphere, particularly 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 data bases for most mountain areas of the world (Barry, 1994).

Particularities of Alpine climate this century

The climate of the Alpine region is characterized by a high degree of complexity, due to the interactions between the mountains and the general circulation of the atmosphere, which result in features, such as, gravity wave breaking, blocking episodes, and foehn winds. A further cause of complexity is to be found in the competing influences of a number of different climatological regimes in the region - Mediterranean, continental, Atlantic, and Polar. Traditionally, the Alps are perhaps the best-endowed mountain system in terms of climatological and environmental data, and it is here that many of the most relevant studies of climate and climate change in mountain regions have been undertaken.

Figure 1 shows the changes in yearly mean surface temperature anomalies this century from the 1951-1980 climatological mean, averaged for eight sites in the Swiss Alps. These observational sites range in altitude from about 569 m above sea level (Zürich) to close to 2500 m (Säntis). The global data of Jones and Wigley (1990) has been superimposed here to illustrate the fact that the interannual variability in the Alps is more marked than on a global or hemispheric scale; the warming experienced since the early 1980s, while synchronous with the global warming, is of far greater amplitude and reaches up close to 1°C for this ensemble average and up to 2°C for individual sites (not shown). This represents roughly a five-fold amplification of the global climate signal in the Alps (see also Diaz and Bradley, 1997). Similar studies for the Austrian Alps (e.g., Auer and Boehm, 1994) and the Bavarian Alps, based on climatological records from the Sönnblick Observatory (Austria) and the Zugspitze (Germany) lead to broadly similar conclusions.

{Insert Figure 1 Here}

Beniston et al. (1994) have undertaken an exhaustive study of climate trends this century in the Swiss Alps. Climate change in the region this century has been characterized by increases in minimum temperatures of about 2°C, a more modest increase in maximum temperatures (in some instances a decrease of maxima in the latter part of the record), little trend in the precipitation data, and a general decrease of sunshine duration through to the mid-1980s. Warming has been most intense in the 1940s, followed by the 1980s; the cooling which intervened from the 1950s to the late 1970s was not sufficient to offset the warming in the middle of the century. The asymmetry observed between minimum and maximum temperature trends in the Alps is consistent with similar observations at both the sub-continental scales (e.g., Brown et al., 1992, for trends in the Colorado Rocky Mountains and neighboring Great Plains locations), and the global scale. Karl et al. (1993) have shown that over much of the continental land masses, minimum temperatures have risen at a rate three times faster than the maxima since the 1950s, the respective anomalies being on the order of 0.84°C and 0.28°C during this period.

Pressure statistics have been compiled as a means of providing a link between the regional-scale climatological variables and the synoptic, supra-regional scale. These statistics have shown that pressure exhibits a number of decadal-scale fluctuations, with the appearance of unusual behavior in the 1980s; in that particular decade, pressure reached annual average values far higher than at any other time this century. The frequency of occurrence of high pressure episodes exceeding a sea-level reduced threshold of 1030 hPa between 1983 and 1992 account for one-quarter of all such episodes this century. The pressure field is well correlated with the North Atlantic Oscillation (NAO) Index - a measure of the strength of flow over the North Atlantic, based on the pressure difference between the Azores and Iceland - for distinct periods of the Swiss climate record (1931 - 1950 and 1971 - 1990) and is almost decorrelated from the NAO Index for the other decades of the century. This is indicative of a transition from one climatic regime to another, dominated by zonal flow when the correlation with the NAO Index is high. In the 1980s, when zonal flow over the North Atlantic was particularly strong, episodes of persistent, anomalously high pressures were observed over the Alps and in southern Europe, particularly during the winter season (Hurrell and van Loon, 1997). This resulted in large positive departures in temperature anomalies and a significant lack of precipitation, particularly in the form of snow, in the Alps. Indeed, much of the strong warming observed since the 1980s and illustrated in Figure 1 can be explained to a large degree by these persistent high pressure anomalies. During this same period in Europe, the Iberian Peninsula was under the influence of extended periods of drought and very mild winters, while northern Europe and Scandinavia were experiencing above-average precipitation (Hurrell, 1995).

Beniston and Rebetez (1995) have shown, that there is not only a time-dependency on observed warming, but also an altitudinal dependency of temperature anomalies. Taking the latter part of the climatological record into consideration, i.e., the 15-year period from 1979 - 1994, they have shown that minimum temperature anomalies exhibit a significant linear relationship with altitude, except at low elevations which are subject to wintertime fog or stratus conditions; the stratus or fog tends to decouple the underlying stations from processes occurring at higher altitudes. The authors have also shown that there is a switch in the gradient of the temperature anomaly with height from cold to warm winters. For warm winters, which represent 7 of the last 15 years, the higher the elevation, the stronger the positive anomaly; the reverse is true for cold winters (accounting for 5 winters during this period). This is illustrated in Figure 2 for the Alpine stations, which represent 39 of the 88 Swiss observational sites which were used in this investigation. The figure provides a measure of the damping of the climate signal as an inverse function of height. The spread of data is the result of site conditions; topography plays a key role in the distribution of temperature means and anomalies, in particular for stations located on valley floors, where temperature inversions are likely to occur which frequently lead to a decoupling of temperatures at these locations from those above the inversion which are closer to free atmosphere conditions. Recent work by Giorgi et al. (1996), based on high-resolution simulations with a limited-area model have led to conclusions broadly consistent with the statistical analysis of Swiss data; an altitudinal dependency of temperature anomalies is perceived in GCM and regional climate model simulations (Diaz and Bradley, 1997; Vinnikov et al., 1996).

{Insert Figure 2 Here}

One of the numerous problems associated with future climate change induced by anthropogenic emissions of greenhouse gases is the behavior of extreme temperatures and precipitation and how these may respond to shifts in the means (Giorgi and Mearns, 1991; Katz and Brown, 1992; Beniston, 2000; IPCC, 1996). Extreme climatological events tend to have a greater impact than changes in mean climate, which is commonly the basic variable for discussing climatic change, on a wide range of environmental and socio-economic systems. Based on the high spatial and temporal density of the Swiss climatological observing network, it has been possible to evaluate how shifts in climate this century have influenced the extremes of temperature at different locations in the Alpine region. Temperature extremes exhibit an asymmetry between the shifts in the lower (minimum) extreme and the upper (maximum) extreme, leading to a changed frequency distribution profile for temperatures. This is illustrated in Figure 3 for the climatological station of Davos, located at 1,590 m above sea level in the eastern part of the Swiss Alps.

{Insert Figure 3 Here}

Detailed studies such as those reviewed here would be necessary elsewhere in the mountain region of the world, primarily to characterize their current climatological characteristics, but also as a means of providing information useful to the climate modeling community. Because of the expected refinements in the physical parameterizations of climate models in coming years, and the probable increase in the spatial resolution of GCMs, the use of appropriate data from high elevation sites will become of increasing importance for model initialization, verification, and intercomparison purposes. The necessity of accurate projections of climate change is paramount to assessing the likely impacts of climate change on mountain biodiversity, hydrology and cryosphere, and on the numerous economic activities which take place in these regions.

Modeling of climatic change in the Alpine region

In terms of modeling studies of mountain climates, 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 for investigating the potential impacts of climate change. Any meaningful climate projection for mountain regions - and indeed for any area of less than a continental scale - needs to consider processes acting from the very local to the global scales. Numerous climatological details of mountains are overlooked by the climate models, making it difficult to predict the consequences of climate change on mountain hydrology, glaciers, or ecosystems (Giorgi and Mearns, 1991; Beniston, 2000). The situation is currently improving with the advent of high-resolution climate simulations, where the spatial scale of GCMs is on the order of 100 km (Beniston et al., 1995; Marinucci et al., 1995). However, much of the research on the potential impacts of climate change in mountain regions require climatological information on scales which are generally far smaller than the typical grid-size of even the highest resolution numerical climate models. As a result, many impacts studies have been constrained by the lack of scenario data of sufficient reliability and quality at the desired scales. It is these scales, however, which are of particular interest to policy makers, especially in the context of the United Nations Framework Convention on Climate Change, whose aim is to limit anthropogenic interference with the climate system and allow its future evolution to be sufficiently slow for ecosystems to adapt naturally to this change.

One solution to this problem resides in a technique in which a regional climate model (RCM), which operates with a much finer spatial definition, makes use of the GCM data as initial and boundary conditions for much more detailed climatological simulations over a region of interest, such as the Alps. The technique has been applied to the Alpine region, in which the RCM is capable of simulating climatic processes in the vicinity of the Alps in much more detail, since it captures the geographical details more precisely with its 20-km horizontal grid than does the GCM with its 120-km grid.

High-resolution climatologies for January and July in both the 'present-day' and the 'double-CO_2' situations have been simulated over the Alps using the RegCM2 RCM of the National Center for Atmospheric Research (NCAR, Boulder, Colorado) and the ECHAM-4 GCM (Marinucci et al., 1995; Rotach et al., 1997). Based on the global information provided by the GCM for a five-year time window for both the present and future climates, RegCM2 has simulated detailed climatologies over the region of interest. To analyze the model performances, the results from these simulations were compared with two observed climatological data sets, namely the 0.5° resolution gridded data of Legates and Wilmott and a dataset from close to 100 observing stations distributed throughout Switzerland. The nested model RegCM2 reproduced several aspects of the Alpine temperature and precipitation climatology but also showed significant deficiencies which are likely to be linked to failings in the initial and boundary conditions provided by ECHAM-4.

{Insert Figure 4 Here}

In the "double-CO_2" simulations (i.e., for the time in which atmospheric concentrations will double with respect to pre-industrial values), generally higher winter temperatures and a more marked increase in summer temperatures appears to be in accord with other studies on global climate change (Figure 4); there are indications that temperature increases more at higher elevations than at lower altitudes (Rotach et al., 1997). Precipitation is also higher and more intense in winter, but much reduced in summer (Figure 5). While the temperature and precipitation changes are within the range of model errors (when compared to observational data), comparing only model simulations for present and future climates reveals trends of temperatures and precipitation which are consistent with greenhouse-gas warming.

{Insert Figure 5 Here}

Impacts of climatic change in mountain regions

Mountain regions are characterized by sensitive ecosystems, enhanced occurences 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 non-viable regions, mountains have in the latter part of the century attracted major economic investments for tourism, hydro-power, and communication routes. In the context of climate change, significant perturbations can be expected to natural systems and these will inevitably have an influence on the economy of mountainous regions.

Examples of systems in mountain areas which could be significantly perturbed by abrupt climate change, in particular hypothesized global warming consecutive to increases in greenhouse gases of anthropogenic origin, are given below.

Impacts on water resources

The sharing of water resources poses immense political problems when major hydrological basins are shared by several different countries, and it is exceedingly difficult to manage the waters of a river which crosses several international boundaries. For example, the Swiss Alps are the source of many of Europe's major rivers, in particular the Rhône, the Rhine, the Inn which feeds into the Danube and the Ticino which flows into the Pô. Rivers originating in Switzerland flow into the North Sea, the Mediterranean, the Adriatic, and the Black Sea. Any uncoordinated control of these river basins by any one country, due to decreased precipitation and increased demand would lead to serious conflictual situations downstream. Such problems would become exacerbated by climate change in sensitive regions.

Simulating precipitation patterns in mountain areas is today exceedingly difficult, because many precipitation events are local or mesoscale in nature and are poorly resolved by even the most advanced RCMs. Predicting the future trends of precipitation over areas as small as the Alps, for example, is practically impossible with present-day GCMs, so that little can be inferred for the impact of global warming on precipitation patterns. However, this is one key parameter which urgently requires quantification, as any significant change in rainfall or snowfall will have wide-ranging effects on natural and economic environments, both within the mountains themselves and far downstream in the river basins which they control.

Impacts on snow, glaciers, and permafrost

The IPCC has attempted to assess some of the potential effects of a warmer atmosphere on the mountain cryosphere. According to a report by the National Research Council (1985), a 1° C increase in mean temperature implies that the present snowline could rise by about 200 m above present levels in the European Alps. Kuhn (1989) has estimated that, for a 3° C warming by the middle of the next century, ice would no longer occur below the 2500 m level in the Austrian Alps, with the consequence that 50% of the remaining ice cover would disappear. It is, however, difficult to estimate the exact response of glaciers to global warming, because glacier dynamics are influenced by numerous factors other than climate, even though temperature, precipitation, and cloudiness are the dominant controlling factors. According to the size, exposure, and altitude of glaciers, different response times can be expected for the same climatic forcing. For example in Switzerland, a number of glaciers are still advancing or are stationary despite a decade of mild winters, warm summers, and lower than average precipitation.

A rise in the snowline would be accompanied by ablation of present permafrost regions. Zimmermann and Haeberli (1989) show that permafrost melting as well as the projected decrease in glacial coverage would result in higher slope instability, which in turn would lead to a greater number of debris and mud slides, and increased sediment loads in rivers.

Impacts on forests and natural ecosystems

Species will react in various manners to global climate change; increases can be expected for some species while others will undergo marked decreases. Under conditions of rapid warming, it is quite likely that certain ecosystems may not adapt quickly enough to respond to abrupt climate changes; this could be the case of forests which may not be able to migrate fast enough, or of species with very local ranges which have nowhere to migrate to. The possibilities of migration of species to higher altitudes, in order to find similar conditions to those of today, will probably be limited by other factors such as soil types, water availability, and the human barriers to migration such as settlements and highways. Analogies with migrations of the past are hazardous at best because of human perturbations to the environment which were not present millenia ago, and because the expected climatic change will be at a rate unprecedented in the last 10,000 years. The disappearence of certain types of protective vegetation cover, particularly forests, from mountain slopes would render these more prone to erosion, mud and rock slides, as well as avalanches.

{Insert Figure 6 Here}

As an illustrative example of potential changes in different mountain regions of the Western Hemisphere, Halpin (1994) has applied an ecosystem model to mountain sites in Costa Rica, California, and Alaska. Figure 6 illustrates the changes in vegetation typology which can be expected following a change in climate marked by a rise in temperature of 3.5 °C and a 10% increase in precipitation. In all three cases, it is seen that not only the vegetation belts shift upwards - with the result that some species at the top of the mountains disappear because of the lack of migration potential - but also that there is considerable competition between species. In this latter case, some species are able to migrate much faster than others, thereby replacing the slower moving species. The overall picture is that, due to both direct extinction resulting from problems of migration, and extinction through inter-species competition, the biological diversity in all three mountain regions diminishes significantly. In Halpin's example, about 33% of plants in Costa Rica undergo substantial changes, close to 66% in California, and a relatively low 22% in Alaska; this latter situation is due to the fact that the edge of the tundra vegetation and snowline is relatively unaffected by a 3-4 °C warming since the annual average temperature would be still well below freezing even after climatic change of the expected amplitude has occurred.

Impacts on mountain economies

The environmental impacts of a warmer atmosphere would have a number of consequences for the regional economy of a mountain region. Increases in debris flows and avalanches would be responsible for greater incidence of damage to buildings and traffic routes, vegetation, and the obstruction of rivers with corresponding flooding. In the severe flooding episode of August 1987 in Central Switzerland, road and rail traffic on one of the densest north-south communication routes across the Alps was severely disrupted. Future increases in such episodes would have severe economic consequences not only for the region itself, but also for all users of such vital communication links. The additional risks due to climate change would sharply raise insurance premiums to cover the higher frequency of damage to property, as well as the basic costs of civil engineering works necessary for the protection of settlements and communication routes. Such costs would weigh heavily upon regional mountain economies.

Tourism may also suffer from climate change in mountain regions; in particular, uncertain snow cover during peak winter sports seasons may discourage tourists to come to the mountains. However, in recent years, numerous winter sports resorts have been facing financial difficulties even during favorable winters. Many are now re-organizing their sports and cultural infrastructure in order to attract vacationers whatever the climatic conditions.

Hydro-electric power is a key element of mountain-based economy in the Alpine regions, as well as in the Rockies and in the Southern Alps of New Zealand. In this latter country, over 70% of electricity is generated by hydro-power (Fitzharris, 1989). Accelerated glacier melting would result in an increase in electricity production and a reduction in water storage requirements, at least until the glaciers find a new equilibrium level. However, if the glacier melting is intense, then river flooding and damage to dam structures may occur, offsetting the temporary 'benefits' of increased storage and production capacities.

Conclusions

The assessment of potential impacts of climatic change in mountain regions is particularly difficult because of the complexity of a number of interrelated factors in regions of complex orography. However, despite the numerous uncertainties associated with regional climatic change in mountain regions, there is today a large consensus concerning the very real threat which abrupt global warming poses to a wide range of environmental, social and economic systems both globally and regionally such as in the Alps. The IPCC (1996) has been instrumental in providing the state-of-the-art information on climatic change and its environmental and economic consequences, so that while science can continue to refine its predictions for the future, there is sufficient material to justify joint international action for reducing the risks related to climatic change and to define strategies for adapting to change as soon as possible, before such actions become much more costly in the future.

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Figure Captions

Figure 1: Yearly-mean surface temperature anomalies averaged for eight high-elevation sites in the Swiss Alps, ranging in altitude from 569 m to 2500 m above sea level. The change in global mean temperature anomalies is given for comparison purposes. The data from 1901-1999 has been smoothed using a five-year running-average

Figure 2: Vertical distribution of minimum temperature anomalies at 39 climatological stations in the Swiss Alps, for both "mild" and "cold" winters experienced during the 15-year period from 1979 - 1994

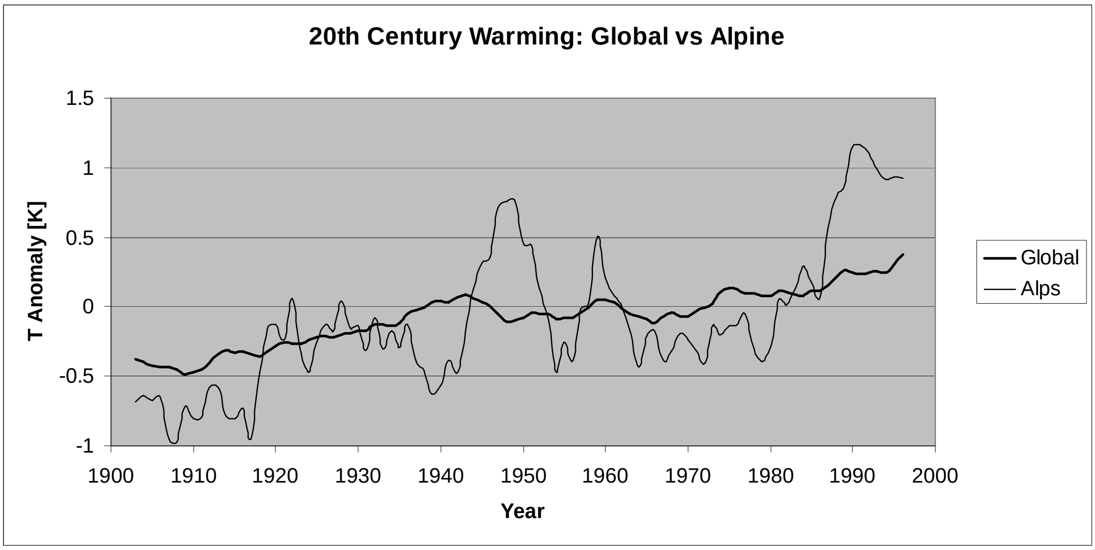
Figure 3: *Upper*: Five-year means of minimum temperature this century at Davos
Lower: Shift in the minimum temperature distribution profile at Davos as a function of the changes in the mean value; two profiles are illustrated, corresponding to the warmest (1991-1994) and coldest (1906-1910) periods of the century, respectively

Figure 4: RCM temperature change in January (left) and July (right), between current and future climate

Figure 5: As Figure 3, except for average daily precipitation changes. Units: mm/day

Figure 6: Shifts in vegetation belts in three mountain regions of the Western Hemisphere representative of tropical (upper), temperate (middle) and boreal (lower) climates, following moderate changes in temperature and precipitation in the next century (adapted from Halpin, 1994).

FIGURE 1



20th Century Warming: Global vs Alpine
1.5
1
0.5
0
-0.5
-1
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1930
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1970
1980
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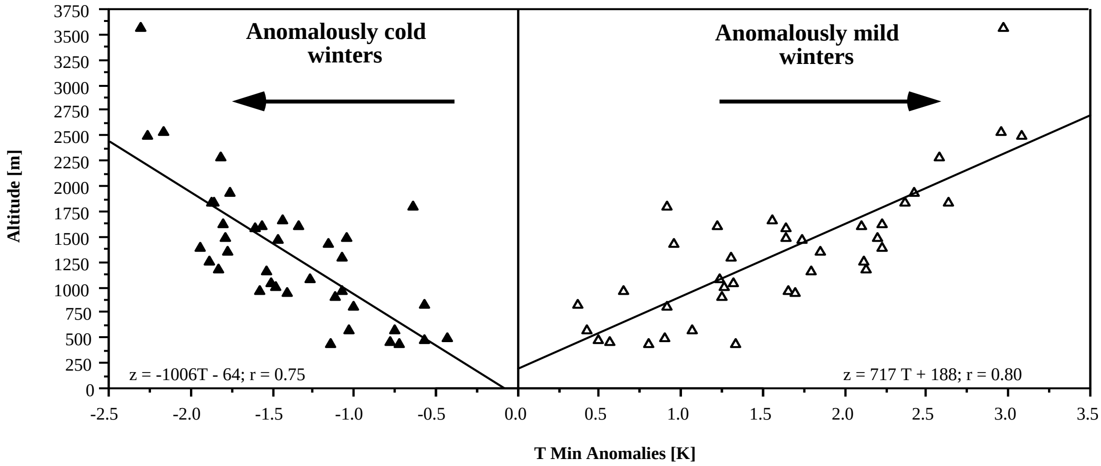
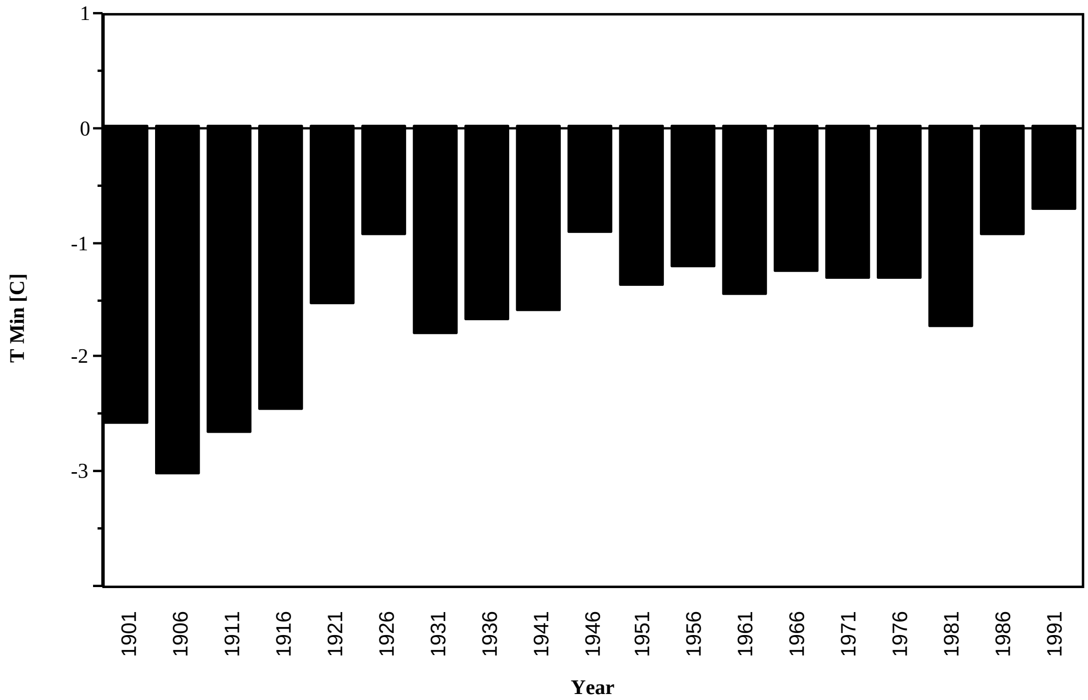
Year
Global
Alps

FIGURE 2

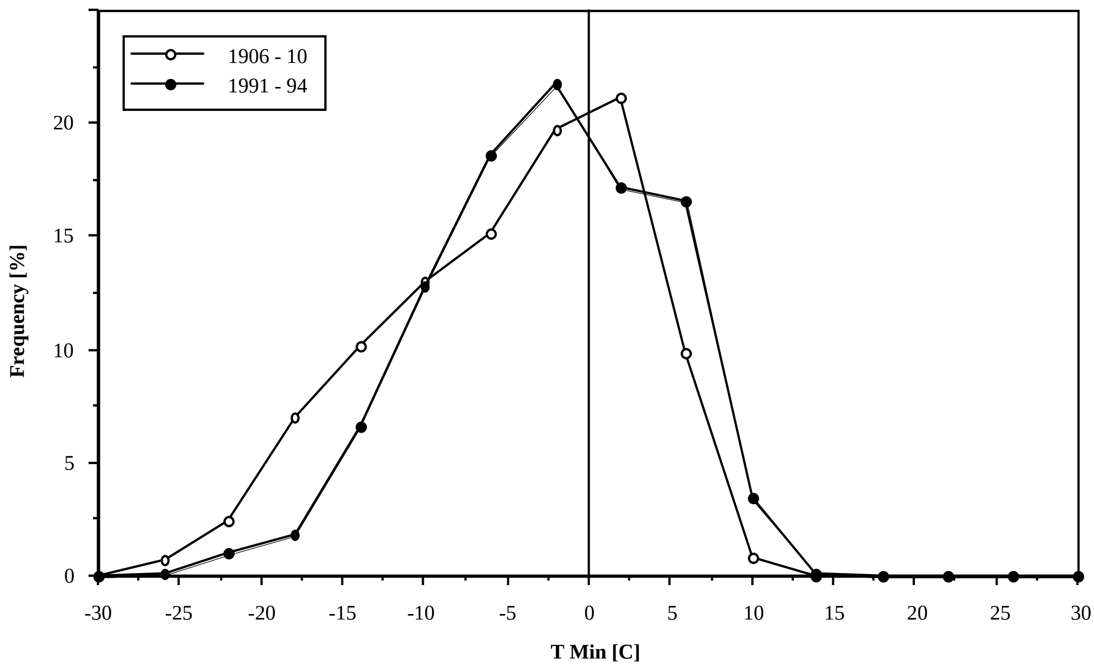


Anomalously cold winters
Anomalously mild winters
z = -1006T - 64; r = 0.75
z = 717 T + 188; r = 0.80
Altitude [m]
T Min Anomalies [K]
3750
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

FIGURE 3



T Min [C]
1
0
-1
-2
-3
1901
1906
1911
1916
1921
1926
1931
1936
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
Year



1906 - 10
1991 - 94
Frequency [%]
0
5
10
15
20
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
T Min [C]

FIGURE 4

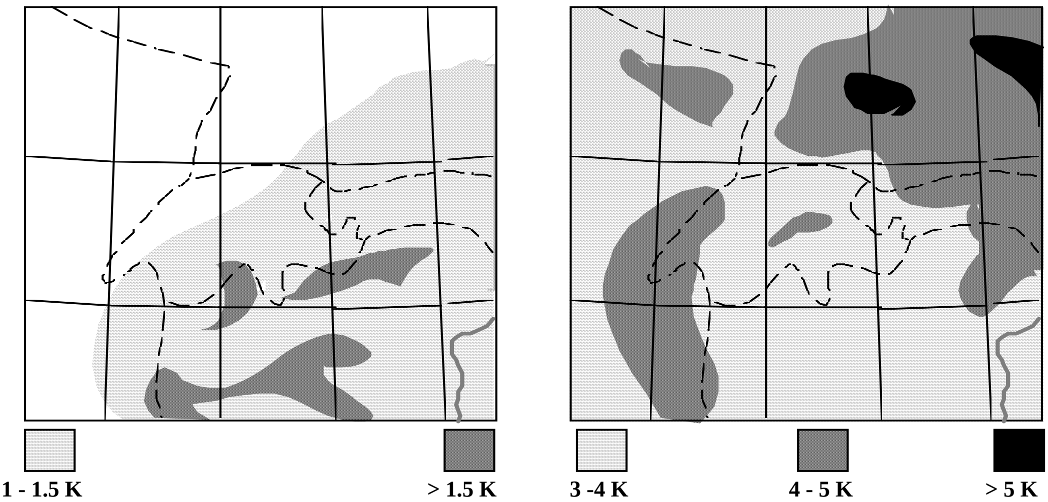


FIGURE 5

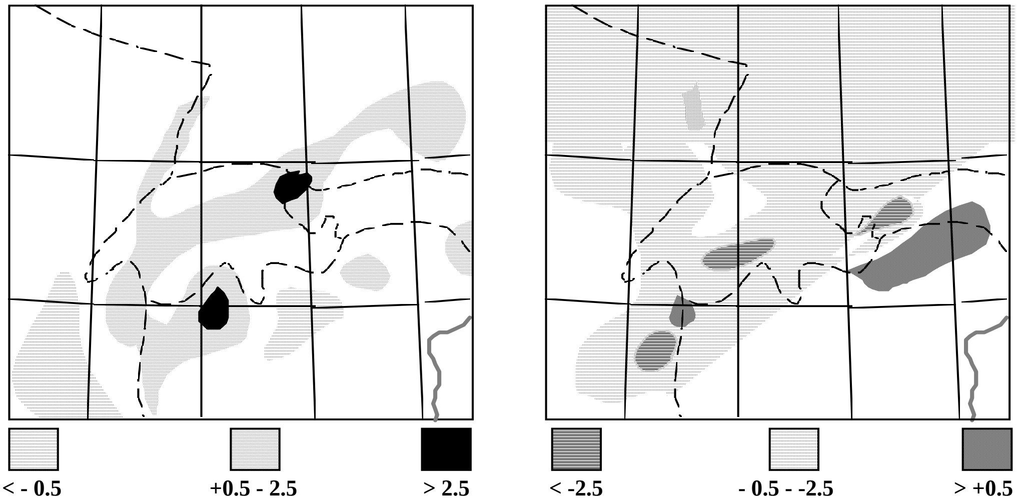
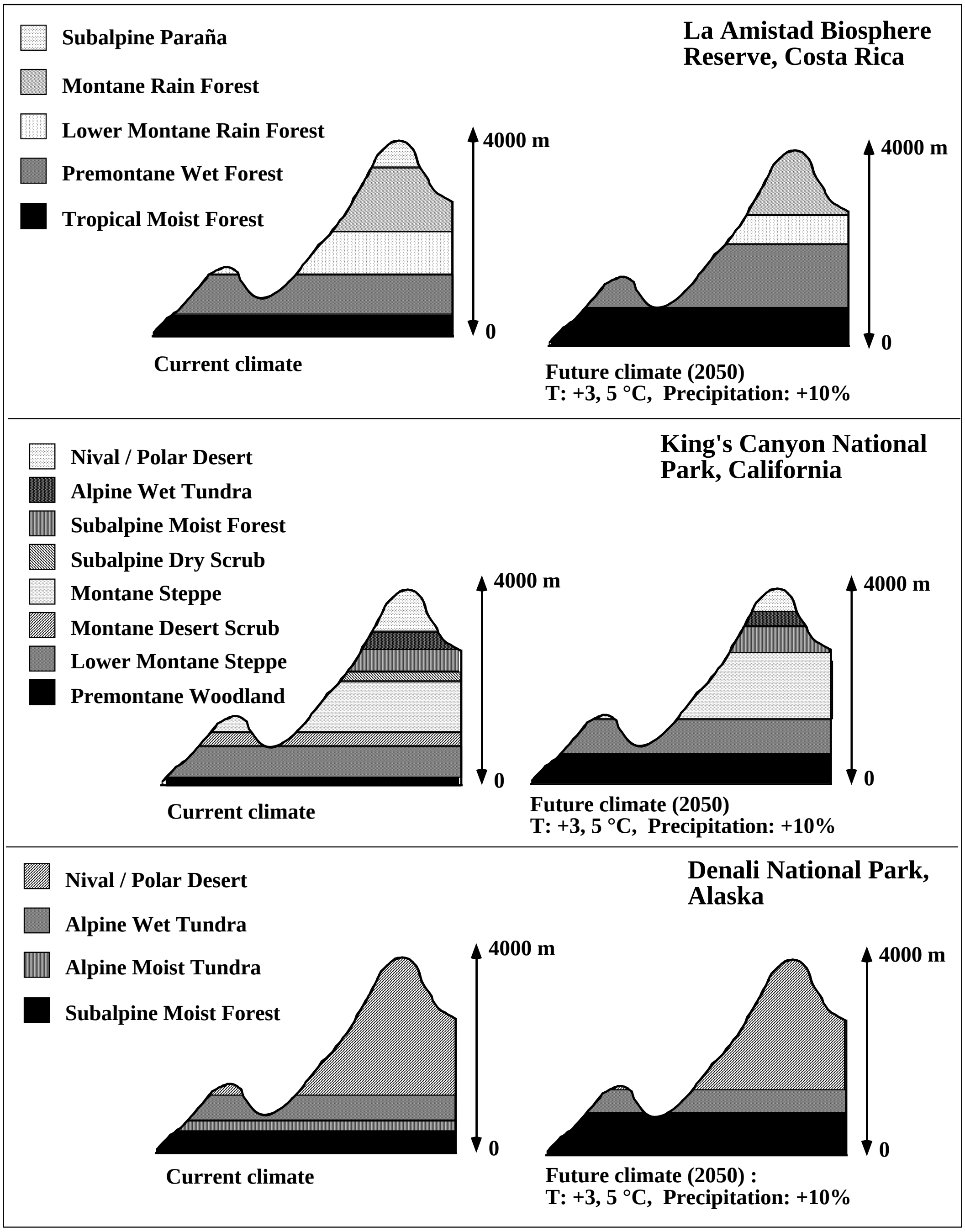


FIGURE 6


La Amistad Biosphere Reserve, Costa Rica
Subalpine Paraña
Montane Rain Forest
Lower Montane Rain Forest
Premontane Wet Forest
Tropical Moist Forest
4000 m
0
Current climate
4000 m
0
Future climate (2050)
T: +3, 5 °C, Precipitation: +10%
King's Canyon National Park, California
Nival / Polar Desert
Alpine Wet Tundra
Subalpine Moist Forest
Subalpine Dry Scrub
Montane Steppe
Montane Desert Scrub
Lower Montane Steppe
Premontane Woodland
4000 m
0
Current climate
4000 m
0
Future climate (2050)
T: +3, 5 °C, Precipitation: +10%
Denali National Park, Alaska
Nival / Polar Desert
Alpine Wet Tundra
Alpine Moist Tundra
Subalpine Moist Forest
4000 m
0
Current climate
4000 m
0
Future climate (2050) :
T: +3, 5 °C, Precipitation: +10%