



Exposure of global mountain systems to climate warming during the 21st Century

D. Nogués-Bravo^{a,b,*}, M.B. Araújo^{c,b}, M.P. Errea^d, J.P. Martínez-Rica^d

^aMacroecology and Conservation Unit, University of Évora, Estrada dos Leões, 7000-730 Évora, Portugal

^bCenter for Macroecology, Institute of Biology, University of Copenhagen, Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark

^cDepartment of Biodiversity and Evolutionary Biology, National Museum of Natural Sciences, CSIC, C/José Gutiérrez Abascal, 2, 28006 Madrid, Spain

^dPyrenean Institute of Ecology, CSIC, Campus de Aula Dei, Apartado 202, 50080-Zaragoza, Spain

Received 27 June 2006; received in revised form 20 November 2006; accepted 20 November 2006

Abstract

We provide an assessment of surface temperature changes in mountainous areas of the world using a set of climate projections at a 0.5° resolution for two 30-year periods (2040–2069 and 2070–2099), using four Intergovernmental Panel for Climate Change (IPCC) emission scenarios and five AOGCM. Projected average temperature changes varied between +3.2 °C (+0.4 °C/per decade) and +2.1 °C (+0.26 °C/per decade) for 2055 and +5.3 °C (+0.48 °C/per decade) and +2.8 °C for 2085 (+0.25 °C/per decade). The temperature is expected to rise by a greater amount in higher northern latitude mountains than in mountains located in temperate and tropical zones. The rate of warming in mountain systems is projected to be two to three times higher than that recorded during the 20th century. The tendency for a greater projected warming in northern latitude mountain systems is consistent across scenarios and is in agreement with observed trends. In light of these projections, warming is considered likely to affect biodiversity (e.g., species extinctions, changes in the composition of assemblages), water resources (e.g., a reduction in the extent of glaciated areas and snow pack), and natural hazards (e.g., floods). Accurate estimate of the effects of climate change in mountain systems is difficult because of uncertainties associated with the climate scenarios and the existence of non-linear feedbacks between impacts.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Mountains; Climate warming; Impact assessment; Exposure rank; Spatial patterns; Uncertainty

1. Introduction

Mountains are amongst the most fragile environments in the world (Diaz et al., 2003). They are a repository of biodiversity, water and other ecosystem services (Korner, 2004; Woodwell, 2004; Viviroli and Weingartner, 2004), and their influence exceeds that of their geographical limits and extends to the surrounding lowlands. Approximately, 26% of the world human population inhabit mountainous regions (Meybeck et al., 2001). Mountains constitute centres of endemism for biodiversity, harbouring endangered

species and ecosystems. Mountains also provide services with tangible economic value as power supply, tourism, or crop and livestock productions. They are also key to shaping regional climates in the surrounding areas. Currently, these environments are affected by different pressures from economic and population growth (Spehn et al., 2002). Other pressures include climate change impacts on alpine species distributions, retreat of glaciers or alteration of hydrological cycles (e.g., Barry and Seimon, 2000; Foster, 2001; Hill et al., 2002; Dyurgerov, 2003; Grabherr, 2003; Konvicka et al., 2003; Wilson et al., 2005; Schröter et al., 2005; Thuiller et al., 2005; Bradley et al., 2006). The magnitude of the expected climate warming has been assessed for particular mountain ranges (e.g., Bradley et al., 2004), but to our knowledge no study has addressed the magnitude of future warming during the 21st century on different mountain systems. Here, a set of

*Corresponding author. Center for Macroecology, Institute of Biology, University of Copenhagen, Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark. Tel.: +45 34627354331; fax: +45 4535322321.

E-mail addresses: dnoques@uevora.pt, dnoques@bi.ku.dk (D. Nogués-Bravo), maraujo@mncn.csic.es (M.B. Araújo), jpmr@ipe.csic.es (J.P. Martínez-Rica).

0.5°-resolution climate data-sets from five Atmosphere–Ocean General Circulation Models (AOGCM) and four Intergovernmental Panel for Climate Change (IPCC) emission scenarios (Special Report on Emission Scenarios—SRES), are used to assess the expected change in surface temperature of 13 mountain systems in the world, between baseline (1961–1990) and two periods in the future (2040–2069 and 2070–2099). We also address two further aims: (i) to examine the statistical significance of any differences found between the projected warming for each mountain group and the warming projected for non-mountain regions within their own latitudinal band; (ii) to rank the magnitude of temperature changes for each mountain group under each emission scenario: what we call ‘exposure ranking’.

2. Data and analyses

The World Mountain Map of UNEP-WCMC (United Nations Environmental Program-World Conservation Monitoring Centre) (Kapos et al., 2000; <http://www.unep-wcmc.org/habitats/mountains/region.html>) was used to delimit the study area (Fig. 1). The mountains identified by UNEP-WCMC were then grouped by continents and bioclimatic regions using the Holdridge classification (Holdridge, 1967). High-latitude mountains belonging to the polar, sub-polar and boreal zones are located between 90°N and 55°N in the New World and between 90°N and 60°N in Eurasia. Mid-latitude mountain systems in the cool temperate and warm temperate zones are located between 55°N–60°N and 25°N, and 25°S and 60°S; low-latitude mountains are located in the tropical zone between 25°N and 25°S. We created 13 mountain groups by taking into account their position within the bioclimatic zones and continents (Fig. 1). Although other classifications are possible, this scheme allows the integration of all UNEP-WCMC mountains in relatively simple and intuitive classes that are consistent with previous bioclimatic classifications of the world (Holdridge, 1967).

Temperature scenarios from transient atmosphere–ocean coupled GCM simulations (CSIRO2, ECHAM4/OPYC3, CGCM2, HadCM3, PCM; see Table 1 for more details)

Temperature scenarios from transient atmosphere–ocean coupled GCM simulations (CSIRO2, ECHAM4/OPYC3, CGCM2, HadCM3, PCM; see Table 1 for more details)

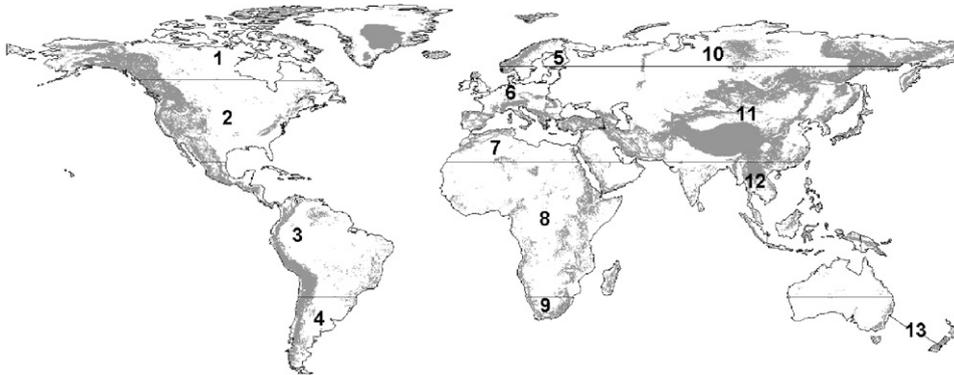


Fig. 1. Mountain areas were delimited following the UNEP-WCMC mountain map (plotted in dark grey): (1) America high-latitude mountains at northern hemisphere (High_NAmerica); (2) America mid-latitude mountains at northern hemisphere (Mid_NAmerica); (3) America low-latitude mountains (Low_America); (4) America mid-latitude mountains at southern hemisphere (Mid_SAmerica); (5) Europe high-latitude mountains (High_Europe); (6) Europe mid-latitude mountains (Mid_Europe); (7) Africa mid-latitude mountains at northern hemisphere (Mid_NAfrica); (8) Africa low-latitude mountains (Low_Africa); (9) Africa mid-latitude mountains at southern hemisphere (Mid_SAfrica); (10) Asia high-latitude mountains (High_Asia); (11) Asia mid-latitude mountains (Mid_Asia); (12) Asia low-latitude mountains (Low_Asia); (13) Australia and New Zealand (AustraliaNZ).

Table 1

A list of AOGCM used by Climatic Research Unit at the University of East Anglia to develop climate change scenarios used herein (0.5° of spatial resolution) to assess the future climate change in mountain environments

Model name	Centre (country)	Reference	Atmospheric resolution	Ocean resolution
ECHAM4/OPYC3	DKRZ (Germany)	Roeckner et al. (1996)	T42 (2.8 × 2.8) L19	2.8 × 2.8 L11
CGCM2	CCCma (Canada)	Flato and Boer (2001)	T32 (3.8 × 3.8) L10	1.8 × 1.8 L29
HadCM3	UKMO (UK)	Gordon et al. (2000)	2.5 × 3.75 L19	1.25 × 1.25 L20
CSIRO Mk2	CSIRO (Australia)	Gordon and O'Farrell (1997)	R21 (3.2 × 5.6) L9	3.2 × 5.6 L21
DOE PCM	NCAR (USA)	Washington et al. (2000)	T42 (2.8 × 2.8) L18	0.67 × 0.67 L32

Atmospheric resolution: horizontal and vertical resolution. The former is expressed either as degrees latitude × longitude or as a spectral truncation with a rough translation to degrees latitude × longitude. An asterisk indicates enhanced meridional resolution in midlatitudes. ZA indicates a zonally averaged model (360° zonal resolution). Vertical resolution is expressed as “Lmm”, where mm is the number of vertical levels.

Ocean resolution: horizontal and vertical resolution. The former is expressed as degrees latitude × longitude, while the latter is expressed as “Lmm”, where mm is the number of vertical levels. An asterisk indicates enhanced horizontal resolution near the Equator. ZA indicates a zonally averaged model for each ocean basin. The following classification of ocean horizontal resolution is used: Coarse: >2°, medium: 2/3° to 2°, Eddy-permitting: 1/6° to 2/3°, Eddy-resolving: <1/6°.

covering emerged land-masses but excluding Antarctica were used. A range of AOGCM and emission scenarios were used as recommended by IPCC (IPCC, 2001). This allows variability in climate change projections to be taken into account. Climate change scenarios were produced by the Climatic Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/~timm/grid/TYN_SC_2_0.html); (Mitchell et al., 2004). Baseline observed surface temperatures for 1961–1990 were used for comparison with future scenarios (New et al., 1999; see also Mitchell et al., 2004).

Four emission scenarios were used as follows. A1FI (global economic) is a fossil fuel intensive world of rapid economic growth, low population growth and rapid introduction of new and more efficient technologies. A2 (regional economic) is a world of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. B1 (global environmental) is a convergent world with rapid change in economic structures, ‘dematerialization’ and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability. B2 (regional environmental) is a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with less rapid, and more diverse technological change but a strong emphasis on community initiatives and social innovation to find local, rather than global solutions. These four scenarios account for ca. 68% of the variation in the 40 emission scenarios published by the IPCC (IPCC, 2001, Table SPM-3a). The 20 climate change scenarios used here (five AOGCM times four emission scenarios) account for 95% of the variability in IPCC climate change scenarios for the 21st century (Mitchell et al., 2004).

To assess future temperature changes in mountain systems the following protocol was utilised. First, we computed surface temperature changes for each one of the 20 future climate scenarios by subtracting them to 1961–1990 baseline temperature values. Then, we averaged temperature changes for the world mountain system as a whole and for each one of the individual mountain groups considered in isolation. Second, we assessed whether differences in temperature changes within emission scenarios for each mountain group were significantly different because of the AOGCMs. Differences were tested with standard analysis of variance (ANOVA). Also, we calculated the standard deviation ($\sigma_{\Delta T}$) of projected temperature changes among AOGCMs within each emission scenario to estimate the inter-model consistency of regional patterns. Consistency was measured as the mean projected warming, $\{\Delta T\}$, across all five AOGCM within each emission scenario divided by its standard deviation ($\{\Delta T\}/\sigma_{\{\Delta T\}}$). Third, we ranked mountain systems on the basis of their estimated temperature change for each emission scenario and then we added the ranks obtained under each emission scenario to develop a synthetic ranking of exposure to

climate change. Fourth, using temperature warming projected for each climate change scenario, we compared statistical differences, using ANOVA tests, between the temperature changes of each group of mountains and the non-mountain land within their latitudinal band.

3. Results

First, the mountain systems of the world are expected to warm in the 21st century, although to differing extents. World-wide, the two most divergent scenarios are A1FI and B1, which predict an average temperature change of between +3.2 °C (+0.4 °C/per decade) and +2.1 °C (+0.26 °C/per decade) for 2055 and +5.3 °C (+0.48 °C/per decade) and +2.8 °C for 2085 (+0.25 °C/per decade). When analyses are carried out by mountain group, the high-latitude mountains of Asia show the greatest increase in average temperatures under the four emission scenarios (2055: +5.0 °C under A1FI (+0.62 °C/per decade) and +3.6 °C under B1 (+0.45 °C/per decade); 2085: +8.4 °C (+0.76 °C/per decade) and +4.8 °C, respectively (+0.43 °C/per decade), while New Zealand and Australian mountains are projected to show the smallest change: 2055–+2 °C under A1FI (+0.25 °C/per decade); and +1.5 °C under B1 (+0.18 °C/per decade); 2080–+3.7 °C (+0.33 °C/per decade); and +1.9 °C, respectively (+0.17 °C/per decade). Results show a latitudinal gradient of temperature change in which those mountains at high and medium latitudes show the greatest temperature rise. These include high-latitude mountains of Asia, previously reported, the high-latitude mountains of North America, mid-latitude mountains of Asia or high-latitude mountains of Europe (see Table 2). Conversely, tropical and mid-latitude mountains in Africa and South America are expected to warm less (see Table 2).

World-wide, the A1FI scenario predicts the greatest average warming, followed by A2, B1 and B2 (Table 2). The difference between the two most divergent scenarios, A1FI and B1, is 1.1 °C in 2055 (+0.13 °C/per decade) and 2.2 °C in 2085 (+0.19 °C/per decade). Differences between these two scenarios also show a marked spatial pattern. For high-latitude Asian mountains, the difference between A1FI and B1 is 1.4 °C in 2055 (+0.17 °C/per decade) and 1.2 °C for Asia mid-latitude mountains (+0.15 °C/per decade) or 1 °C (+0.12 °C/per decade) for North America high-latitude mountain systems. In contrast, mid-latitude mountains in South America, (+0.7 °C; +0.09 °C/per decade), and New Zealand–Australian mountain systems, (+0.7 °C; +0.09 °C/per decade), show smaller differences in relation to emission scenarios. More specifically, polar and boreal mountains of eastern Asia, Alaska and northern Canada are predicted to show the greatest variation due to alternative socio-economic pathways for the future (see Fig. 2).

Second, although each emission scenario predicts different temperature changes, only high-latitude mountains of Europe, Scandinavian mountains, show statistically

Table 2

Predicted average temperature change for different emission scenarios, the standard deviation (σ_T) of projected temperature among AOGCMs within each emission scenario, the p -values showing the statistical differences between each mountain group and the lowlands in the same latitudinal band, and the rank to climate change exposure

Mountain group (number in Fig. 1)	A1FI	A2	B1	B2	σ_T	A1FI-B1	p -value	Rank
2055								
High_Asia (10)	5.0	3.8	3.6	3.6	0.7	1.4	>0.05	1
High_NAmerica (1)	4.1	3.3	3.0	3.1	0.5	1.1	>0.05	2
High_Europe (5)	3.6	2.9	2.7	2.8	0.4	0.9	>0.05	3
Mid_Asia (11)	3.8	2.9	2.7	2.7	0.6	1.1	>0.05	4
Mid_Africa (9)	3.4	2.6	2.4	2.4	0.5	1.0	>0.05	5
Mid_NAmerica (2)	3.3	2.5	2.3	2.3	0.5	1.0	>0.05	6
Mid_Europe (6)	3.3	2.5	2.3	2.3	0.5	1.0	>0.05	7
Low_America (3)	2.7	2.1	1.8	1.8	0.4	0.9	>0.05	8
Low_Africa (8)	2.7	2.1	1.8	1.8	0.4	0.9	>0.05	9
Mid_Safrica (9)	2.4	1.8	1.6	1.6	0.4	0.8	>0.05	10
Low_Asia (12)	2.3	1.8	1.6	1.6	0.4	0.7	>0.05	11
Mid_Samerica (4)	2.2	1.8	1.5	1.6	0.3	0.7	>0.05	12
AustraliaNZ (13)	2.0	1.5	1.3	1.3	0.3	0.7	<0.05	13
Average	3.2	2.4	2.1	2.2	0.5	1.1		
2085								
High_Asia (10)	8.4	6.6	4.8	5.0	1.7	3.4	>0.05	1
High_NAmerica (1)	6.7	5.4	3.8	4.1	1.3	2.5	>0.05	2
Mid_Asia (11)	6.5	5.0	3.6	3.8	1.4	2.7	>0.05	3
High_Europe (5)	5.9	4.8	3.4	3.7	1.1	2.2	>0.05	4
Mid_NAmerica (2)	5.4	4.2	3.0	3.2	1.1	2.3	>0.05	5
Mid_Africa (9)	5.5	4.3	2.9	3.2	1.2	2.3	>0.05	6
Mid_Europe (6)	5.3	4.1	2.9	3.1	1.1	2.2	>0.05	7
Low_Africa (8)	4.6	3.6	2.4	2.6	1.0	2.0	>0.05	8
Low_America (3)	4.6	3.5	2.4	2.6	1.0	2.0	>0.05	9
Mid_Safrica (9)	4.4	3.4	2.3	2.4	1.0	1.9	>0.05	10
Low_Asia (12)	3.9	3.1	2.1	2.3	0.9	1.7	>0.05	11
Mid_Samerica (4)	3.7	3.0	2.0	2.1	0.8	1.6	>0.05	12
AustraliaNZ (13)	3.7	2.9	1.9	2.1	0.8	1.6	<0.05	13
Average	5.3	4.1	2.8	3.1	1.1	2.2		

significant differences ($p < 0.05$) within each emission scenario because of the great inter-model variability of future warming. Also, results show a good agreement in relation to inter-model consistency of regional patterns. In all cases, the values of the consistency index are above 2 (recommended threshold by IPCC 2001 Report is 1).

Third, and using the ranking index (Table 2), polar, subpolar and boreal mountain systems are projected to warm most, while tropical mountains are projected to warm least. The rank is stable between the two time periods considered and only mid-latitude mountains of Asia and high-latitude mountains of Europe change their ranks. Specifically, mountain ranges located in the northeast of Asia such as the Chukot or Kolyma ranges, the Kamchatka mountainous areas and mountains of Baffin Island and the Queen Elizabeth Islands mountains in northern Canada show the largest exposure to global warming: 5–7 °C temperature increase in 2055 under A1FI scenario and 4–5 °C under B1 (see Fig. 2). Finally, only New Zealand–Australian mountain systems differ significantly from the increase of temperatures of emerged lands in their latitudinal band. The other groups of mountain systems do not show significant differences

relating to global warming (see “ p -values” column of Table 2).

4. Discussion

The projected amount of warming for mountain areas in the 21st century is greater than that recorded in the 20th century; this pattern is consistently observed when different emission scenarios and AOGCM are considered. A global comparison of surface and free-air temperatures recorded at high elevations (Pepin and Seidel, 2005) reported a median warming at the surface of +0.13 °C/decade in the second half of the 20th century (+0.65 °C in the past 50 years). Similarly, an increase of +0.6 °C was reported for the tropical Andes from 1939 to 1998, +0.1 °C/decade (Vuille and Bradley, 2000) and an increase of +0.9 °C for the Pyrenees from 1880 to 1950 (Bucher and Dessens, 1991; an increase of +0.11 °C/decade). In contrast, the average projected warming for global mountain systems as a whole up to 2055 (A1FI and B1) ranges from +3.2 °C (+0.4 °C/decade) to +2.1 °C (+0.26 °C/decade); in other words, the magnitude of future projections, per decade, is two to three

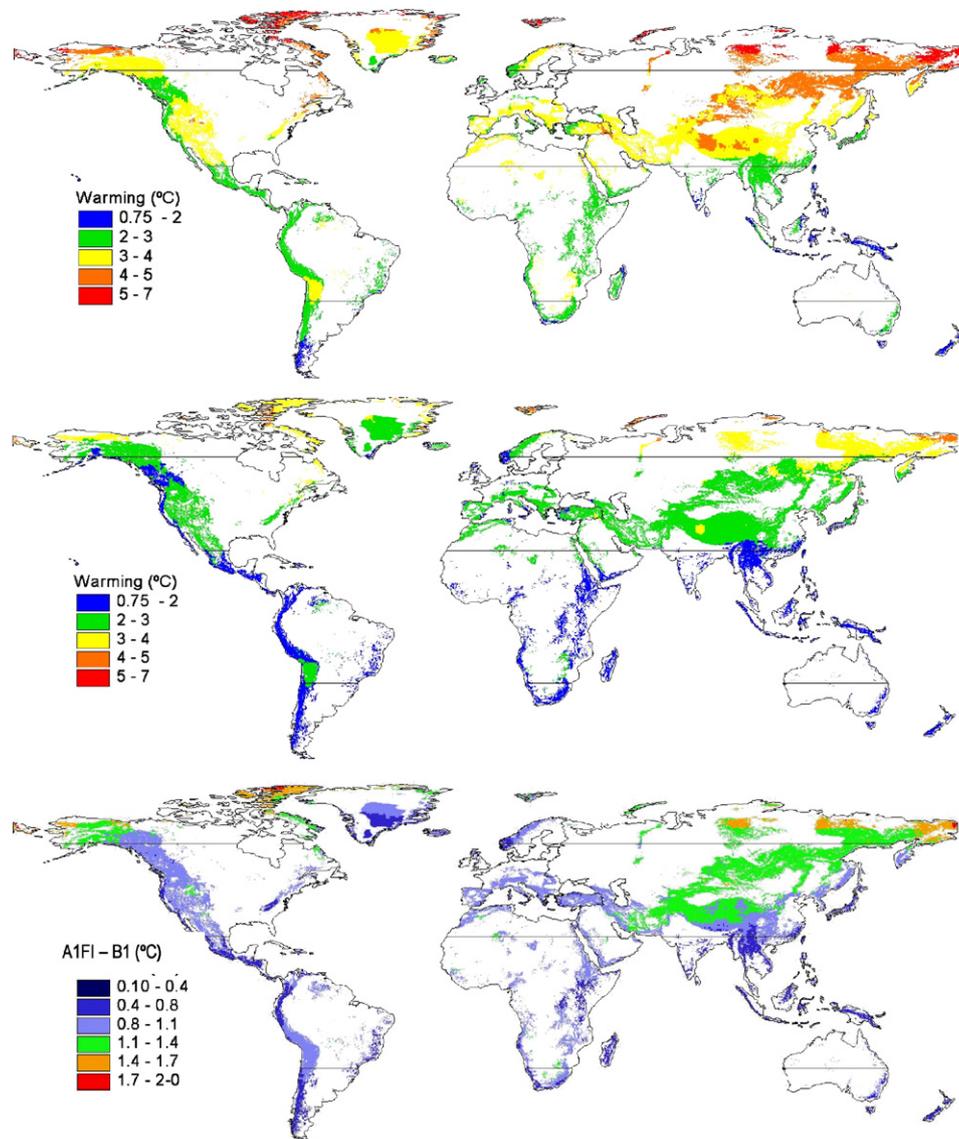


Fig. 2. Projected warming for 2055 (A1FI—upper; B1—middle) after averaging the five AOGCM. There is a clear latitudinal warming pattern from arctic and boreal mountains to tropical mountains in both scenarios. Bottom map shows the difference between the two most divergent scenarios (A1FI and B1) showing also a longitudinal pattern in the exposure of global mountain systems to warming because of the emission scenario.

times greater than that recorded by Pepin and Seidel (2005) for the 20th century.

In accordance with the projections described here, both authors reported a significant and greater warming during the 20th century in mountains located at high latitudes in the Northern Hemisphere, in agreement with previous global analyses (Jones and Moberg, 2003). Moreover, differences between recorded and projected warming are greater for polar and boreal mountain systems than for tropical systems. Although a comparable latitudinal gradient of temperature warming was recorded during the second half of the 20th century, the magnitude of warming during this period was lower for Northern Hemisphere mountains than that projected for the 21st century. For example, an increase of $+0.7^{\circ}\text{C}$ ($+0.14^{\circ}\text{C}/\text{decade}$) was observed for North American mountains from

1948 to 1998 (Pepin and Seidel, 2005), whereas an increase of $+2.7^{\circ}\text{C}$ ($+0.34^{\circ}\text{C}/\text{decade}$) is projected for 2055 under the most conservative emission scenario, B1 (warming calculated after averaging groups 1 and 2; see Fig. 1).

We have not observed significant differences in future warming between mountains and lowlands located in the same latitudinal band, except for New Zealand and Australian mountain systems. Previous studies have suggested that the recorded increase in temperature has been more intense in areas of high elevation (Beniston et al., 1997; Diaz and Bradley, 1997); however, other studies failed to reach the same conclusion (e.g., Vuille and Bradley, 2000; Pepin, 2000). In a recent comparison of surface and free-air temperatures at high elevations, Pepin and Seidel (2005) failed to find any significant relationship between the magnitude of temperature trends and

elevation, despite the findings of the studies cited above. This lack of agreement between different studies indicates the need for future research on this topic to improve existing projections of climate change in mountainous areas.

The impact of climate warming on environmental and socio-economic systems in mountainous areas should be expected over the next century on the basis of climate-change impacts recorded in the past (Beniston, 2003) and the degree of warming projected for the future. Among the currently observed biological impacts, we must consider those impacts related to upward shifts in vegetation belts to higher elevations, northward advances in the geographical ranges of species in the northern hemisphere, and changes in the compositions of several communities (see Walther et al. (2002), Parmesan and Yohe (2003), and Root et al. (2003) for a synthesis of the future impacts of climate change on biodiversity). For example, an investigation involving 4 years of experimental warming and nutrient addition revealed changes in the dominance hierarchies, community structure, and diversity of an alpine biodiversity hotspot in southern Norway (Klanderud and Totland, 2005). Walther et al. (2005) also reported that changes in vegetation in the southeast Swiss Alps have accelerated since 1985, consistent with the effects of climate change. In addition, a recent European study that modelled the distributions of plants in relation to climate (Thuiller et al., 2005) reported that mountain species, specifically those located near the Mediterranean Basin, are disproportionately sensitive to climate change (up to 60% species loss by 2080).

Other potential biological impacts have received less attention compared to the well-known effect of elevation-related changes in biodiversity resulting from climate warming. In light of the projected warming reported here, we suggest that a change in biogeographic types is likely to occur: mountain ecosystems may change to thermophilic types. Thus, arctic mountains may become increasingly boreal, while boreal mountains may change to temperate types, temperate to Mediterranean, etc. This pattern of change will be more difficult to detect than the upwards shifting pattern because it involves colonization by new species across large distances; however, such changes have been documented previously over long time spans, such as the colonization of ice-free areas by plants during the Holocene (Delcourt and Delcourt, 1991).

Second, the fact that glaciers are retreating and decreasing in volume is unquestionable, especially since the end of the 1980s: 7000 km² of mountain glaciers disappeared in the last four decades of the 20th century (Dyurgerov, 2003). Other local and regional studies have reported similar trends (Diaz and Graham, 1996). For example, the extent of glaciers in the European Alps has decreased by 30–40% during the 20th century (Haerberli and Beniston, 1998), and a decrease of 25% has been recorded for glaciers in the Canadian Rockies over the same period (Luckman and Kavanagh, 2000). Therefore, it

is only to be expected that there will be a gradual disappearance of many glaciers over the coming decades. Similarly, significant reductions in snow pack have been reported (Breiling and Charmanza, 1999; Beniston et al., 2003; López-Moreno, 2005).

Third, the influence of glaciers and snow pack on the hydrological cycle is of key importance, particularly in regions where the water supply is mainly derived from snowmelt or ice (Barnett et al., 2005), although this influence is also of importance in tropical areas (Bradley et al., 2006). Mountain regions supply a large proportion of the world's population with fresh water. In humid areas, mountains supply up to 20–50% of the total discharge, while in arid areas this figure is 50–90%, with extremes of over 95% (Viviroli and Weingartner, 2004). A change from snow-fed to rain-fed regimes associated with climate warming (i.e., less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring) implies increasing variability in discharge (López-Moreno and García-Ruiz, 2004), possible modifications of reservoir management patterns, and the increased necessity for dam construction (López-Moreno et al., 2005). Climate warming will also impact on hydropower generation. For example, on the basis of moderate climate-change scenarios, we must expect changes in discharge regimes in the future, leading to unstable regional trends in hydropower potential and reductions in hydropower potential of 25% or more for southern and southeastern European countries (Lehner et al., 2005). In addition to the impacts of warming on hydrological cycles, the synergetic relationships between temperature, precipitation, and changes in land use are likely to have a significant effect on water resources.

Fourth, the impact of the projected warming may well vary spatially because the economic role of mountains varies significantly between developed and developing countries. Mountains in developed countries are usually managed via a sub-exploitation model that involves the intensive use of productive areas and the abandonment of traditional activities. For example, ski resorts might well experience a reduction in the length of the snow season (Breiling and Charmanza, 1999), leading to important reductions in profits. In contrast, mountains in developing countries remain centres of crop and livestock production. Accordingly, changes in the timing of specific chilling periods will affect crop yields and lead to an increase in xeric conditions that is likely to degrade herbaceous pastures and grazing livestock (Slingo et al., 2005). Finally, Tol et al. (2004) propose that climate change is likely to impact more severely on poorer countries because their adaptive capacity is lower, although the authors note that the geographical pattern of vulnerability is complex because it is not solely related to per capita income.

In summarizing the possible impacts of climate change on mountainous areas, we emphasise that different features (e.g., biodiversity, hydrological resources) in mountainous areas do not show a common response to projected global warming. A sector-by-sector analysis undertaken by Hitz

and Smith (2004) found a range of negative, positive, linear, and parabolic relationships between a global-scale increase in mean temperature and resulting benefits. Nevertheless, Hitz and Smith (2004) predict that a warming of mean temperature beyond 3–4 °C is likely to result in increasingly adverse impacts in sectors such as agriculture, water resources, terrestrial ecosystem productivity, and human health, although their study was not designed for mountainous areas. In light of current projections of climate warming reported herein and the 3–4 °C threshold reported by Hitz and Smith (2004), the adverse impacts in the sectors analysed by these authors are also likely to occur in mountainous areas. Specifically, for 2055, seven of the 13 considered mountain systems show a projected warming greater than 3 °C under the A1Fi emission scenario, mainly those systems located in the arctic, boreal, or temperate zones of Asia, North America, and Europe. However, only the arctic and boreal mountains of Asia and North America (two of 13 systems) go beyond this threshold under the most conservative emission scenario (see Table 2).

Previous studies have highlighted the degree of uncertainty involved in different climate-change scenarios and the use of different methodological approaches to assess potential impacts (see Thuiller et al. (2004) for an example of the uncertainty involved in predicting the risk of species extinction). Assuming that temperature decreases by 0.6 °C for every 100-m increase in elevation (Del Barrio et al., 1990), isotherms will move upward by between 380 and 550 m in the mid-latitude mountain systems of Europe and North America (calculated for the two most divergent scenarios: B1 and A1f1). Thus, the potential consequences of climate change in terms of the upward movement of vegetation belts or changes in the extent of the glaciated area below the equilibrium line altitude (ELA) will vary markedly depending upon the choice of emission scenario.

In addition, the nature of the predicted effects are complicated by the synergetic and non-linear relationships among related impacts. For example, as climate warming would lead to an increase in vegetation productivity, it could also act as a secondary force in the process of vegetation recovery (e.g., see Vicente-Serrano et al. (2005), for an account of the effect of human management on vegetation). The afforestation process involves a reduction in erosion rates and a reduction of water availability for human use because of the consumption of water by plants (Beguiria et al., 2003). In summary, accurate estimation of the effects of climate change is difficult because of the uncertainties associated with climate scenarios and because of non-linear feedbacks between impacts.

The climate-change scenarios developed here, with a spatial resolution of 0.5°, provide a broad-brush perspective of predicted future temperatures for different groups of mountain ranges. The coarse resolution of AOGCMs may be capable of capturing the mean climate behaviour, showing consistent regional patterns (Giorgi and Bi, 2005) and similar temperature changes to those predicted

by Regional Climate Models (RCMs) (Deque et al., 2005). But these earlier studies also highlight the fact that the behaviour is different for precipitation and that the model bias is twice as large as the climate response (these previous studies compared global high-resolution data with Limited Area Model climate-change projections for Europe). In addition, AOGCMs are not usually successful in reproducing higher-order statistics and extreme values or adequately reproducing the elevational dependency of changing temperature (Giorgi et al., 1997).

The coarse spatial resolution of the climate-change scenarios used here does not enable a consideration of the complex topographical patterns of temperature change and other regional climate features. Regional and local projections based on RCM (see Giorgi and Mearns (1991) for a pioneering manuscript in this regard) or statistical downscaling techniques (Murphy, 2000) should be considered in future research to account for local patterns of climate change within individual mountain ranges. Regional approaches provide consistent improvements in the spatial detail of simulated climate compared to AOGCMs. Regional projections of the impacts of climate change are therefore required by researchers, planners and decision-makers to develop specific adaptation and mitigation strategies.

While new models are developed to fine-tune and improve regional-scale projections of climate change, the coarse assessment reported here provides a first step towards an understanding of the potential impacts of climate change and the spatial patterns of change on mountain environments during the course of the current century.

Acknowledgements

Research by DNB and MBA is funded by the EC FP6 ALARM project (GOCE-CT-2003-506675). MBA is a “Ramón y Cajal” Research Fellow funded by the Spanish Ministry of Education and Science. Thanks Dr. Scott Butler (www.scienceanager.com), for English style revision of the manuscript. We would like to extend our gratitude to López-Moreno for his suggestions on cryosphere impacts and to two anonymous reviewers for their helpful comments. The Map of the Mountain of the world was supplied by UNEP-WCMC.

References

- Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438 (7066), 303–309.
- Barry, R.G., Seimon, A., 2000. Research for mountain area development: climatic fluctuations in the mountains of the Americas and their significance. *Ambio* 29, 364–370.
- Beguiria, S., López-Moreno, J.I., Lorente, A., Seeger, M., García-Ruiz, J.M., 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. *Ambio* 32 (4), 283–286.

- Beniston, M., Diaz, H.F., Bradley, R.S., 1997. Climatic change at high elevation sites: an overview. *Climatic Change* 36, 233–252.
- Beniston, M., 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* 59 (1–2), 5–31.
- Beniston, M., Keller, F., Goyette, S., 2003. Snow pack in the Swiss Alps under changing climatic conditions: an empirical approach for climate impact studies. *Theoretical and Applied Climatology* 74, 19–31.
- Bradley, R.S., Keimig, F., Díaz, H.F., 2004. Projected temperature changes along the American cordillera and the planned GCOS network. *Geophysical Research Letters* 31, L16210.
- Bradley, R.S., Vuille, M., Díaz, H.F., Vergara, W., 2006. Threats to water supplies in the tropical Andes. *Science* 312 (5781), 1755–1756.
- Breiling, M., Charmanza, P., 1999. The impact of global warming on winter tourism and skiing: a regionalised model for Austrian snow conditions. *Regional Environmental Change* 1 (1), 4–14.
- Bucher, A., Dessens, J., 1991. Secular trends of surface temperatures at an elevated observatory in the Pyrenees. *Journal of Climate* 4, 859–868.
- Del Barrio, G., Creus, J., Puigdefábregas, J., 1990. Thermal seasonality of the high mountain belts of the Pyrenees. *Mountain Research and Development* 10, 227–233.
- Delcourt, H., Delcourt, P., 1991. *Quaternary Ecology: A Paleocological Perspective*. Chapman & Hall, New York, NY.
- Deque, M., Jones, R.G., Wild, M., Giorgi, F., Christensen, J.H., Hassell, D.C., Vidale, P.L., Rockel, B., Jacob, D., Kjellstrom, E., de Castro, M., Kucharski, F., van den Hurk, B., 2005. Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results. *Climate Dynamics* 25, 653–670.
- Diaz, H.F., Graham, N.E., 1996. Recent changes in tropical freezing heights and the role of sea surface temperature. *Nature* 383 (6596), 152–155.
- Diaz, H.F., Bradley, R.S., 1997. Temperature variations during the last century at high elevation sites. *Climatic Change* 36, 253–279.
- Diaz, H.F., Grosjean, M., Graumlich, L., 2003. Climate variability and change in high elevation regions: past, present and future. *Climatic Change* 59 (1–2), 1–4.
- Dyurgerov, M., 2003. Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle. *Journal of Hydrology* 282, 164–176.
- Flato, G.M., Boer, G.J., 2001. Warming asymmetry in climate change experiments. *Geophysical Research Letters* 28, 195–198.
- Foster, P., 2001. The potential negative impacts of climate change on tropical montane cloud forests. *Earth Science Review* 55, 73–106.
- Giorgi, F., Mearns, L.O., 1991. Approaches to the simulation of regional climate change—a review. *Reviews of Geophysics* 29, 191–216.
- Giorgi, F., Hurrell, J.W., Marinucci, M.R., Beniston, M., 1997. Elevation dependency of the surface climate change signal: a model study. *Journal of Climate* 10, 288–296.
- Giorgi, F., Bi, X., 2005. Updated regional precipitation and temperature changes for the 21st century from ensembles of recent AOGCM simulations. *Geophysical Research Letters* 32, L21715.
- Gordon, H.B., O'Farrell, S.P., 1997. Transient climate change in the CSIRO coupled model with dynamic sea ice. *Monthly Weather Review* 125, 875–907.
- Gordon, C., Cooper, C., Senior, C.A., Banks, H.T., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., Wood, R.A., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics* 16, 147–168.
- Grabherr, G., 2003. Overview: alpine vegetation dynamics and climate change—a synthesis of long-term studies and observations. In: *Alpine Biodiversity in Europe*, Springer, Berlin.
- Haerberli, W., Beniston, M., 1998. Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27, 258–265.
- Hill, J.K., Thomas, C.D., Fox, R., Telfer, M.G., Willis, S.G., Asher, J., Huntley, B., 2002. Responses of butterflies to twentieth century climate warming: implications for future ranges. *Proceedings Royal Society London B* 269, 2163–2171.
- Hitz, S., Smith, J., 2004. Estimating global impacts from climate change. *Global Environmental Change Part A* 14 (3), 201–218.
- Holdridge, L.R., 1967. *Life Zone Ecology*. Tropical Science Center, San Jose, Costa Rica.
- IPCC Third Special Report, 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.
- Jones, P.D., Moberg, A., 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and update to 2001. *Journal of Climate* 16, 206–223.
- Kapos, V., Rhind, J., Edwards, M., Ravilious, C., Price, M.F., 2000. *Developing a Map of the World's Mountain and Forests*. Forests in Sustainable Mountain Development: A State-of-Knowledge Report for 2000. CAB International, Wallingford.
- Klanderud, K., Totland, O., 2005. Simulated climate change altered dominance hierarchies and diversity of an alpine biodiversity hotspot. *Ecology* 86, 2047–2054.
- Konvicka, M., Maradova, M., Benes, J., Fric, Z., Kepka, P., 2003. Uphill shifts in distribution of butterflies in the Czech Republic: effects of changing climate detected on a regional scale. *Global Ecology and Biogeography* 12, 403–410.
- Korner, C., 2004. Mountain biodiversity, its causes and function. *Ambio Supplement* 13, 11–17.
- Lehner, B., Czisch, G., Vassolo, S., 2005. The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energy Policy* 33, 839–855.
- López-Moreno, J.I., García-Ruiz, J.M., 2004. Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. *Hydrological Sciences Journal* 49, 1–16.
- Lopez-Moreno, J.I., 2005. Recent variations of snowpack depth in the central Spanish Pyrenees. *Arctic Antarctic and Alpine Research* 37, 253–260.
- López-Moreno, J.I., Beguería, S., García-Ruiz, J.M., 2005. The management of a large mediterranean reservoir: storage regimens of the Yesa Reservoir, Upper Aragon River Basin, Central Spanish Pyrenees. *Environmental Management* 34 (4), 508–515.
- Luckman, B., Kavanagh, T., 2000. Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio* 29, 371–380.
- Meybeck, M., Green, P., Vörösmarty, C., 2001. A new typology for mountains and other relief classes: an application to global continental water resources and population distribution. *Mountain Research and Development* 21, 34–45.
- Mitchell, T.D., Carter, T.R., Jones, P., Hulme, M., New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Report of Tyndall Centre for Climate Change Research, Working paper 55, 30pp.
- Murphy, J., 2000. Predictions of climate change over Europe using statistical and dynamical downscaling techniques. *International Journal of Climatology* 20, 489–501.
- New, M., Hulme, M., Jones, P., 1999. Representing twentieth-century space-time climate variability. Part I: development of a 1961–90 mean monthly terrestrial climatology. *Journal of Climate* 12, 829–856.
- Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421, 37–42.
- Pepin, N.C., 2000. Twentieth century change in the climate record for the Front Range, Colorado, USA. *Arctic Antarctic and Alpine Research* 32 (2), 135–146.
- Pepin, N.C., Seidel, D.J., 2005. A global comparison of surface and free-air temperatures at high elevations. *Journal of Geophysical Research* 110, D03104.
- Roekner, E., Oberhuber, J.M., Bacher, A., Christoph, M., Kirchner, I., 1996. ENSO variability and atmospheric response in a global coupled atmosphere–ocean GCM. *Climate Dynamics* 12, 737–754.
- Schröter, D., Cramer, W., Leemans, R., Araújo, Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.H., 2005. Ecosystem service supply and vulnerability to global change in Europe. *Science* [Doi:10.1126/science.1115233](https://doi.org/10.1126/science.1115233) *Science*.

- Slingo, J.M., Challinor, A.J., Hoskins, B.J., Wheeler, T.R., 2005. Introduction: food crops in a changing climate. *Philosophical Transactions of the Royal Society B—Biological Sciences* 360, 1983–1989.
- Spehn, E.M., Messerli, B., Körner, C., 2002. A global assessment of mountain biodiversity: synthesis. In: *Mountain Biodiversity. A Global Assessment*, Parthenon, Boca Raton.
- Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C., Pounds, J.A., 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421, 57–60.
- Thuiller, W., Araújo, M.B., Pearson, R.G., Whittaker, R.J., Brotons, L., Lavorel, S., 2004. Uncertainty in predictions of extinction risk. *Nature* 430, 33.
- Thuiller, W., Lavorel, S., Araújo, M.B., Sykes, M., Prentice, I.C., 2005. Climate change threats to plant diversity in Europe. *Proceedings National Academy Science USA* 102 (23), 8245–8250.
- Tol, R.S.J., Downing, T.E., Kuik, O.J., Smith, J.B., 2004. Distributional aspects of climate change impacts. *Global Environmental Change* 14, 259–272.
- Vicente-Serrano, S., Lasanta, T., Romo, A., 2005. Analysis of spatial and temporal evolution of vegetation cover in the Spanish Central Pyrenees: role of Human management. *Environmental Conservation* 34 (6).
- Viviroli, D., Weingartner, R., 2004. Hydrological significance of mountains: from regional to global scale. *Hydrological Earth Systems Science* 8 (6), 1016–1029.
- Vuille, M., Bradley, R.S., 2000. Mean annual temperature trends and their vertical structure in the tropical Andes. *Geophysical Research Letters* 27, 3885–3888.
- Walther, G., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. *Nature* 416, 389–395.
- Walther, G.R., Beissner, S., Burga, C.A., 2005. Trends in the upward shift of alpine plants. *Journal of Vegetation Science* 16, 541–548.
- Washington, W.M., et al., 2000. Parallel Climate Model (PCM): control and transient simulations. *Climate Dynamics* 16, 755–774.
- Wilson, R.J., Gutierrez, D., Gutierrez, J., Martinez, D., Agudo, R., Monserrat, V.J., 2005. Changes to the elevational limits and extent of species ranges associated with climate change. *Ecology Letters* 8, 1138–1146.
- Woodwell, G.M., 2004. Mountains: top down. *Ambio Supplement* 13, 35–38.