Report

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Climate Change in Mediterranean Mountains during the 21st Century

Mediterranean mountain biomes are considered endangered due to climate change that affects directly or indirectly different key features (biodiversity, snow cover, glaciers, run-off processes, and water availability). Here, we provide an assessment of temperature, precipitation, and spring precipitation changes in Mediterranean mountains under different emission scenarios (Special Report on Emission Scenarios) and Atmosphere-Ocean-Coupled General Circulation Models for two periods: 2055 (2040–2069 period) and 2085 (2070–2099). Finally, the future climate trends projected for Mediterranean mountains are compared with those trends projected for non-Mediterranean European mountain ranges. The range of projected warming varies between +1.4°C and 5.1°C for 2055 (+1.6°C and +8.3°C for 2085). Climate models also project a reduction of precipitation, mainly during spring (−17% under A1fi and −4.8% under B1 for 2085). On the contrary, non-Mediterranean European mountains will not experience a reduction of annual and spring precipitation. Implications of predicted climate change for both human and physical features are coupled in an integrated framework to gain a broad perspective on future trends and their consequences.

INTRODUCTION

Threats to Mediterranean mountains include the retreat of glaciers, reductions of snow pack, changes in the hydrological cycle, and the upward shift of species distributions and vegetation belts (1–5). The impacts of climate change upon mountains (6) and their influence goes beyond that of just their geographical limits because they are repositories of ecosystem services, such as water, which are also used by people inhabiting lowlands. Future implications of climate change on Mediterranean mountains may well change their role as a water repository and affect electrical power supply or endemic species. The mountains are also the location of tourism, having recreational, sporting, and aesthetic value. Over centuries, Mediterranean mountains have been greatly modified by human civilizations (7), changing land use (agriculture, stockbreeding, or forestry) and impacting ecosystems in different ways; therefore, anthropogenic forces have played a key role in shaping their environmental character. However, the growing speed and magnitude of human pressure factors as climate change would exceed the resilience of ecosystems. So, assessing the potential impact of future climate change seems to be a keystone in environmental research.

European mountain and Mediterranean ecosystems are more prone to increases in the vulnerability of ecosystem supply due to global change (8) than other European ecosystems (e.g., declines in soil fertility and water availability and increased risk of forest fires). Thus, the Mediterranean mountains seem to suffer the double jeopardy of being mountains and being located near the Mediterranean basin. There are a number of initiatives already in place to improve the description of patterns and mechanisms characterizing space-time climate variability in the Mediterranean and to identify the forces likely to be responsible for the observed changes (e.g., medCLIVAR http://clima.casaccia.enea.it/medclivar/). Also, reducing the impacts of global warming in the Mediterranean mountains in the 21st century will require additional efforts to identify and implement the most effective adaptation and mitigation strategies (9). Since the 1960s, Atmosphere-Ocean General Circulation Models (AOGCMs) provided appropriate simulations of the climate at a coarse scale and its response to greenhouse gases (10, 11). More recently (12), new models to fine tune the projections of climate change at regional scale have been developed (Regional Climate Models, [RCMs]), but many areas, such as several sectors of the Mediterranean arc, have not yet had enough RCM projections to provide reliable estimates of climate change impacts and their uncertainties. Thus, the scientific community is committed to offer, as RCMs are being developed, a broad picture of future trends of climate change to social and economic agents, including the uncertainty that emerges from climate change predictions.

Currently, projections of future climates may vary according to two main choices: the choice of the climate model (there is a plethora of AOGCMs and RCMs) and the choice of scenarios of future greenhouse gas (13). Both AOGCMs and RCMs are mathematical models that use equations to numerically simulate changes in climate as a response to several forces (14), for example, greenhouse gas emissions. The AOGCMs are the best tool to estimate climate changes across large spatial scales, and RCMs simulate better regional spatial patterns of climate change because of the inclusion of fine-scale parameters such as topographical complexity. The most commonly used emission scenarios are those published by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emission Scenarios (SRES) (13). These scenarios are based on descriptions of alternative worlds (narrative storylines) where changes in population, energy, technology, economy, and land use are allowed to vary quantitatively in concert with the assumptions taken for storylines. However, the spatial patterns and the magnitude of the predicted climate changes differ substantially not only with the SRES but also with the AOGCMs (13). This causes projections of future climates to be highly variable and impacts stemming from climate change uncertain. Strategies have been recommended to deal with this kind of variability, namely using as large a combination of different AOGCMs or RCMs and SRES as possible, to encompass a broad range of possible predicted changes (15). Although AOGCMs are more suited for providing global rather than regional assessments of climate change impact, they do provide a relative assessment of the magnitudes of temperature changes across different regions. As such, they are useful tools for exploring broad-scale impacts and help to target the needs for further research and adaptation.

Here, we use five high-resolution AOGCMs (HadCM3, GCM2, NCAR-PCM, CSIRO2, and ECHAM4/OPYC3; 0.5 degrees resolution), and four future socio-economic scenarios (SRES: A1fi, A2, B1, B2) to assess the climate change and the uncertainty in the predictions in mountain environments located in the Mediterranean Basin for the 2055 (2040–2069) and 2085 (2070–2099) periods with respect to the baseline period 1961–1990. Three variables were analyzed: mean annual temperature, annual precipitation, and spring precipitation. The

Figure 1. Mountainous areas within the Mediterranean region are shown in dark grey. Other European non-Mediterranean mountains are plotted in mid-grey. The assessment of climate change for the 21st century comprises the mountainous areas of the Mediterranean basin, and includes the Pyrenees (1), Apennines (2), Dinaryc Alps (3), Pindhos (4), Taurus (5), or Atlas (6) and other small mountain zones. Mountain areas have been delimitated following the UNEP-WCMC Mountain delimitation.

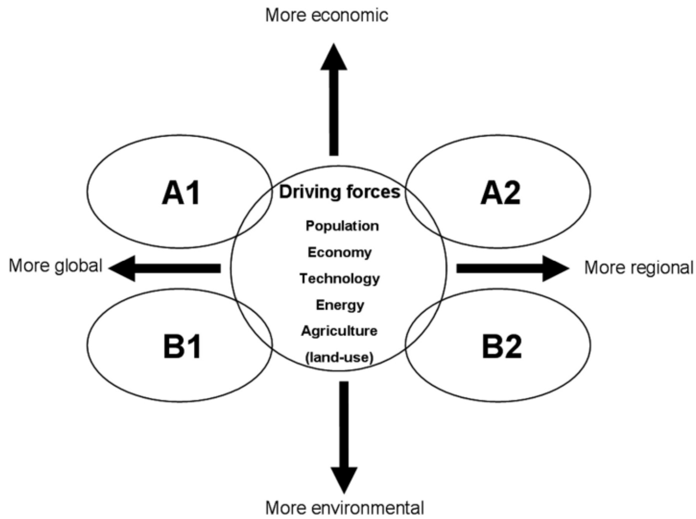

Figure 2. Typology for the SRES scenarios (10): A1fi scenario belongs to the A1 family of scenarios and it specifically features intensive use of fossil fuels. A1 family scenarios describe a future world of very rapid economic growth, a global population that peaks midcentury and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Human fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines. B1 storyline and scenario family describes a convergent world with the same global population, that peaks midcentury and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

same outputs of a set of six RCMs are compared to those provided by AOGCMs for the Pyrenean range as a case study to assess if the magnitude of the expected changes differ noticeably. We ask whether the high-resolution AOGCMs used herein are able to properly project the future mean climate for each mountain range. We also compare the mean projected climate change for the Mediterranean mountain systems with the mean estimates for non-Mediterranean European mountains. Finally the future implications of climate change upon Mediterranean mountains are discussed.

DATA AND METHODS

Mountainous sectors were identified (Fig. 1) using the United Nations Environmental Program World Conservation Monitoring Conference (UNEP-WCMC) delimitation of mountains of the world (16). We considered the Pyrenees, Apennines, Dinaryc Alps, Pindhos, Taurus, and Atlas and other small ranges as mountains belonging to the Mediterranean basin. The data were developed at 1-km pixel resolution using different topographic features, including altitude, slope, and altitudinal range (see http://www.unepwcmc.org/habitats/mountains/region.html for more details).

A set of global, high-resolution (0.5 degrees), gridded datasets ("grids") of monthly climate information covering land-masses based on climatological observations from transient coupled AOGCM simulations was used (17). The data were created by the University of East Anglia's Climate Research Unit and is freely available from http://www.cru.uea.ac.uk/~timm/grid/TYN_SC_2_0.html. Five AOGCMs were used: CSIRO2 (18), ECHAM4/OPYC3 (19), CGCM2 (20); HadCM3 (21), and the NCAR-PCM (22). Baseline mean temperatures (1961–1990) were developed by Mitchell et al. (17).

Because of the lack of RCMs for the entire region, the accuracy of the AOGCMs used here to project climate change in mountains was assessed for a case study: the Pyrenees. Thus, a set of six RCMs driven by the AOGCM HadAM3H at a resolution of 0.44–0.5 degrees for the European continent was used to calculate the mean changes and their spatial patterns on precipitation and temperature for the A2 scenario for 2085. The six RCMs were then compared with the outputs derived directly from the AOGCM HadCM3 (the most similar to HadAM3H used for RCMs). The RCMs were developed by different institutions collaborating through the PRUDENCE project. They are: HIRHAM (DMI), HIRHAM (METNO), HADCM3 (HC), RCAO (SMHI), REGCM (ICTP), and PROMES (UCM) models. A detailed description of the used models can be found in http://prudence.dmi.dk.

The SRES report provides a comprehensive set of 40 socioeconomic futures and provides an assessment of their consequences in terms of anthropogenic emissions of greenhouse gases and other pollutants. Following Mitchell et al. (20), we used A1FI, A2, B1, and B2 (for descriptions see Fig. 2). The combination of 5 AOGCM and 4 SRES produced 20 climate change scenarios that are thought to account for a great part of the variability in climate change projections (near 95%) (17).

Analyses to assess the changes in annual temperature, annual precipitation, and spring precipitation during the 21st century used the following protocol. First, each variable was calculated for the periods 2040–2069 (2055) and 2070–2099 (2085) for each combination of AOGCM and emission scenario. Then, climate changes were measured for each of the 20 climate scenarios by subtracting them from the values of the 1961–1990 baseline period for Mediterranean mountains. To summarize, the changes projected are averaged over the five AOGCM for that

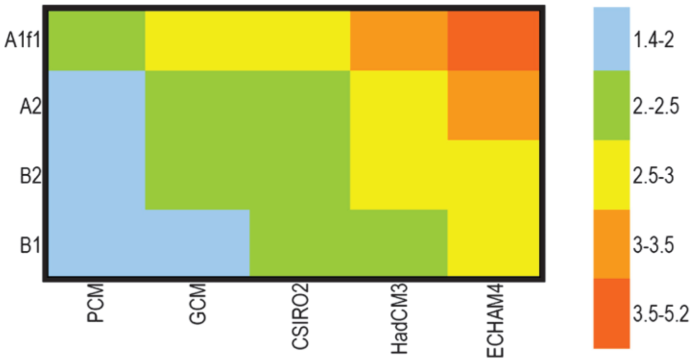

Figure 3. Degree of temperature change (degrees Celsius) for different combinations of AOGCM and SRES. Colors represent changes in temperature.

Table 1. Projected average change of temperature (ΔT, °C), annual precipitation (ΔP, % mm $^{-1}$) and spring precipitation (ΔP, % mm spring^{-1}). Each value for all of the four emissions scenarios is the average of the five AOGCMs for that particular SRES. Projected changes are those from the period 1961–1990 to 2040–2069 (the baseline period and the 2055 period) and from 1961–1990 to 2070–2099 (2085).

Year	SRES	ΔT (°C)	ΔP (%mm $^{-1}$)	ΔP (% mm spring^{-1})
2055	A1	3.2	–5.9	–11.3
	A2	2.5	–4.3	–10.6
	B1	2.3	–2.5	–5.8
	B2	2.3	–2.0	–6.1
2085	A1	5.2	–13.0	–17.0
	A2	4.0	–10.4	–14.4
	B1	2.8	–5.7	–4.8
	B2	3.0	–5.3	–5.5

particular SRES. Thus, temperature-averaged changes (ΔT in °C) and precipitation and spring precipitation changes (ΔP and ΔPSPR, respectively, in terms of percentage) for each emission scenario were calculated to obtain a measure of climate change for 2055 and 2085. Analyses were done for whole areas delimitated as mountain zones by UNEP-WCMC as a set and then for specific Mediterranean mountain ranges (see Fig. 1). Finally, we compared statistical differences using analysis of variance tests between predicted climate changes for Mediterranean mountains and for the mountains of the rest of Europe.

RESULTS

Mediterranean mountains are expected to warm in all climate projections used, but there is an important level of variability across AOGCM and emission scenarios (Fig. 3). For 2055, the lowest warming was predicted by NCAR-PCM_B1, +1.4°C, whereas the largest warming was predicted by ECHAM4_A1fi, +5.1°C. The same model simulations predicted the lowest and highest warming for 2085, although the difference between the two projections was greater for 2085 (+1.6°C and +8.6°C, respectively). Predicted warming differed between the emissions scenarios used. Averaging over the five AOGCMs (Table 1), the A1fi scenario produced the largest warming in Mediterranean mountains (+3.1°C and +5.2°C for 2055 and 2085, respectively; 2055: 1.1 σ_T; 2085: 2.0 σ_T) followed by A2 (+2.5°C and +4°C; 2055, 0.49 σ_T; 2085, 0.87 σ_T), B1 (+2.3°C and +2.8°C; 2055, 0.8 σ_T; 2085, 1.1 σ_T) and B2 (+2.3°C and +3°C; 2055, 0.5 σ_T.; 2085, 0.73 σ_T). Finally, similar warming is projected among Mediterranean mountain ranges (Table 2).

Predicted changes of precipitation differed noticeably among AOGCMs and emission scenarios. Practically all models indicate a decline in precipitation. For 2055, the highest reduction of annual precipitation was predicted by ECHAM4_A1fi, –12.5%, whereas CSIRO_B1 projected an increase of 0.9%. A similar pattern was recorded for 2085, where the highest and lowest reduction was predicted by ECHAM4_A1fi and CSIRO_B1, respectively, although the difference between the two projections was greater for 2085 (–23% and –1.4%, respectively). Averaging over the five AOGCMs, the A1fi scenario produced the largest reduction in Mediterranean mountains (–6% and –13% for 2055 and 2085, respectively; 2055, 31 σ_T; 2085, 51 σ_T) and the B1 the lowest one (Table 1). Regional trends show similar reductions (Table 2). Averaging again over the five AOGCMs (Table 2), the highest and lowest reductions were predicted for the Taurus under A1fi for 2055 (–14.8%) and the Dynaric Alps (–8.8%), respectively.

For 2055, the highest reduction of spring precipitation was predicted by ECHAM4_A1fi, –22.6%, whereas the lowest one was predicted by PCM_B1, –3%. The same pattern was recorded for 2085, where the highest and lowest reduction was predicted by ECHAM4_A1fi and PCM_B1, respectively, although the difference between the two projections was greater for 2085 (–32% and –0.6%, respectively). Predicted reduction of spring rainfall differed between the emission scenarios used. Averaging over the five AOGCMs, the A1fi scenario produced the largest reduction in Mediterranean mountains (–11.3% and –17% for 2055 and 2085, respectively; 2055, 13 σ_T.; 2085, 18 σ_T) and the B1 the lowest one (see Table 1). Regional trends, averaging over the five AOGCMs, show that the highest and lowest reductions were predicted for the Taurus under A1fi for 2055 (–8.8%) and the Dynaric Alps (–2.3%), respectively.

Both AOGCMs and RCMs project similar changes for the three analyzed variables in the Pyrenees by 2085. Projected warming using the AOGCM HadCM3 is +4.2°C and +3.2°C under A2 and B2, respectively. The average warming projected by the RCMs is +3.5°C and +2.5°C under A2 and B2, respectively (driven by HadAM3H for the same SRES scenarios). Similarly, the reduction of annual precipitation projected by the AOGCM is –18.9% for A2 and –10% for B2, and the average reduction projected by the RCMs is –13% and –9%, respectively. Finally, for the spring precipitation, the reduction projected by the AOGCM is –21% for A2 and –16% for B2, and the average reduction projected by the RCMs is –16% and –8%, respectively.

The warming across the 20 gridded climate change scenarios was slightly larger for non-Mediterranean European mountains than for Mediterranean ones (see Fig. 4). On the contrary, only Mediterranean mountains will suffer the reduction of annual and spring precipitation.

DISCUSSION

A general warming trend in the mountains of the Mediterranean Basin should be expected in the 21st century based on the climate change scenarios used here. The magnitude of this warming varies in relation to the economical, political, and technological future evolution of our societies. As shown in Figure 4, a world with very rapid economic growth and intensive fossil fuel use (A1fi) yields the warmest climate change scenario (+3.1°C in 2055 and +5.2°C in 2085). Even when we use the most optimistic scenario, the expected warming rates (+2.2°C and +2.8°C under B1 in 2055) will become markedly more intense than the observed 0.75°C warming for the Mediterranean basin reported by Giorgi (23, 24) for the 20th century. Similarly, predictions for the 21st century are much larger than the +0.9°C warming observed, for example, in the Pyrenees during 20th century (25). Also, climate models project

Table 2. Projected average change for each mountain range of temperature (ΔT, °C), annual precipitation (ΔP, % mm y^{-1}) and spring precipitation (ΔP, % mm $spring^{-1}$) for each emission scenario over the five AOGCMs. Projected changes are those from the period 1961–1990 to 2040–2069 (the baseline period and the 2055 one) and from 1961–1990 to 2070–2099 (2085).

	SRES	Pyrenees	Apennines	Dinaric Alps	Pinthos	Taurus	Atlas
2055							
ΔT (°C)	A1fi	3.3	3.1	3.4	3.1	3.2	3.1
	A2	2.5	2.3	2.6	2.5	2.5	2.4
	B1	2.4	2.2	2.4	2.3	2.3	2.2
	B2	2.3	2.1	2.4	2.3	2.3	2.2
ΔP (% mm $^{-1}$)	A1fi	–5.3	–6.2	–2.3	–3.4	–8.8	–5.3
	A2	–2.8	–4.4	–1.2	–2.7	–7.3	–3.6
	B1	–1.7	–3.8	0.4	–0.1	–4.1	–2.5
	B2	–1.4	–2.7	1.0	0.5	–3.7	–2.3
ΔP (% mm $spring^{-1}$)	A1fi	–13.5	–13.6	–8.8	–12.6	–14.8	–8.8
	A2	–9.1	–6.3	–3.6	–5.6	–12.3	–7.3
	B1	–7.7	–9.0	–5.6	–3.9	–6.1	–5.2
	B2	–8.4	–7.2	–4.5	–3.2	–7.2	–6.3
2085							
ΔT (°C)	A1fi	5.3	4.9	5.5	4.9	5.3	5.5
	A2	4.0	3.7	4.1	3.9	4.1	4.2
	B1	3.1	2.9	3.2	3.0	3.2	3.2
	B2	3.0	2.8	3.1	2.9	3.2	3.1
ΔP (%mm $^{-1}$)	A1fi	–10.5	–9.1	–6.9	–12.4	–22.4	–13.8
	A2	–8.8	–7.4	–5.2	–10.9	–16.2	–11.3
	B1	–4.0	–4.2	–1.8	–5.6	–9.4	–7.8
	B2	–3.9	–3.0	–1.8	–5.0	–9.9	–8.1
ΔP (% mm $spring^{-1}$)	A1fi	–13.6	–14.9	–8.2	–22.1	–22.1	–12.4
	A2	–12.7	–13.9	–7.2	–19.0	–21.2	–10.6
	B1	–6.9	–5.5	–0.6	–2.0	–5.9	–7.3
	B2	–4.2	–4.9	–1.2	–6.4	–8.8	–6.1

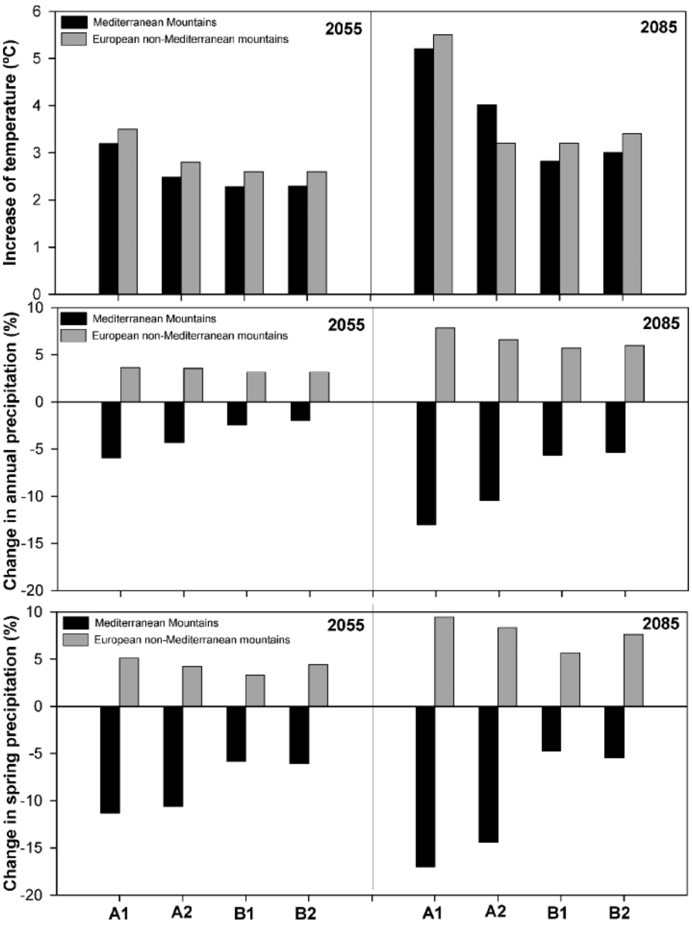

Figure 4. Projected average change of temperature, annual precipitation, and spring precipitation (ΔP, % mm/spring) for each emission scenario. Projected changes are those from the period 1961–1990 to 2040–2069 (the baseline period and the 2055 one) and from 1961–1990 to 2070–2099 (2085). Black bars correspond to mountains located in the Mediterranean while grey bars correspond to European non-Mediterranean mountains.

reductions of annual and spring precipitation in the mountains of the Mediterrranean Basin (e.g., –11.3% and –17% during spring under A1fi for 2055 and 2085, respectively), and this trend is specific to Mediterranean mountains within European mountain ranges (see Fig. 4). So, Mediterranean mountain ecosystems (structure, functions, and services) will likely be subjected to an intensive transformation in the coming decades, even assuming the most conservative estimations.

Presently, the scientific community has reported that the warming detected during the 20th century has affected different features of ecosystems. An approximate +3°C future warming would have multiple adverse impacts upon the sea level, agriculture, water resources, human health, energy, terrestrial ecosystems productivity, forestry, biodiversity, and marine ecosystems productivity (see 24 for a review paper on climate change impacts at a global scale). More specifically, in the Mediterranean mountains, some studies have suggested that changes in temperature and precipitation would lead to a shift toward vegetation types currently found under drier and warmer conditions in Mediterranean mountains (28). Transformation of vegetation belts, for example, has been reported in the Spanish Central Range (29) where high-mountain grassland communities dominated by *Festuca aragonensis*, typical of the Cryoro-Mediterranean belt, are being replaced by shrub patches of *Juniperus communis* ssp. alpina and *Cytisus oromediterraneus* from lower altitudes. Altitudinal changes in the distributions of butterflies species have also been reported within the same mountain range (30). In the Apennines, bird species distributions have changed in the last 20 years (31), and both diversity and composition of plant species have suffered significant transformations (32). Climate warming may imply drastic changes in the ranges of species, potentially leading species inhabiting the upper belts to extinction. A recent study modeling distributions of European plants in relation to climate (33) also reported that mountain species, namely those located near the Mediterranean basin, were disproportionably sensitive to climate change (approximately 60% species potentially lost by 2085), although the coarse resolution used requires that these results are interpreted cautiously. Taking into account the warming predicted here, we would expect, for example, an upward migration of temperatures and its associated vegetation belts ranging from 380 m and 510 m (calculated using the two most divergent scenarios: B1 and A1fi) if a temperature reduction of 0.6°C (34) 100 m^{-1} is assumed.

Climate change is also bound to impact deeply on the criosphere realm at high altitudes. Many glaciers are known to be disappearing (35), and there is also evidence that snow pack in the Pyrenees and the Alps, for example, is decreasing (see 36). The expected upward displacement of the isotherm 0°C will enhance melting rates, whereas a decrease in precipitation will impact on snow and ice: both processes will lead to a negative energy and mass balance of snow, permafrost, and glaciers with several hydrological consequences related to the amount and timing of run-off and peak discharge in rivers. However, the magnitude of the expected climate change on the criosphere will show a large spatial heterogeneity since it will result from a complex synergistic response to global warming and local topographical conditions (37). Some of the described changes will not only be a consequence of climatic change. Land use and other factors, which have not been considered in this study, will play a significant role in balancing or realizing the hydrological and ecological consequences expected under greenhouse climatic conditions.

Besides the consequences of warming on physical or biological patterns and processes, the effects of climate change on social and economic aspects should be taken into account. Mountains provide different economical services to their populations and those in neighboring lowlands: for example, water, wood, power supply, food, and tourism. In European Mediterranean mountains the synergy between agricultural land abandonment, reforestation, reduction of livestock pressure, and climate change could lead to a reduction of pastures due to an extension of forest and scrub (38). Also, the reforestation process implies a reduction of water availability due to plant water consumption (39), explaining the loss of around 30% of the average annual discharge. Other impacts of climate warming on hydrological processes have significant social and economic consequences, for example, the reduction of snow cover on river regimes. Decreasing snow cover implies a change from snow-fed to rain-fed regimes, increasing the intensity and variability of winter discharges (40) and decreasing the runoff in spring. The decrease in water availability during the latter will be aggravated by the reduction of spring precipitation. This reduction will necessitate modification of water management and dam operation schemes, based on the catchments of a large volume of water in winter and spring in order that there is a supply during the irrigation season, which normally lasts from the middle of spring to September (41). Snow pack decrease would also have consequences for the economic viability of many ski resources, although technology to provide artificial snow may well reduce a part of this impact in the resorts located at high altitude.

Mediterranean mountains in developing countries would suffer other possible impacts due to their different social and economic conditions. These mountain systems are highly populated (around 300 hab km^{-2} in western Atlas) (42) because of the diversity of resources created by elevation gradients. For example, reductions in spring rainfall and melt water flows would produce a soil moisture deficit, which could limit any increase in crop yields resulting from temperature increase. Crops such as maize (43), an important summer crop in the Atlas valleys, may suffer as a result. Equally, fruit trees require a specific chilling period that may not be met by higher temperatures. Increases in xeric conditions due to global warming may well degrade and reduce the extension of herbaceous pastures, which accompanied by growing of grazing pressure, will favor higher erosion rates (44).

Adaptation and mitigation strategies for climate change are required to reduce these possible impacts on the provision of ecosystem services for society. However, to reach these objectives there is a need to conduct coarse quantitative estimates of the impacts, to assess the variability of the forecasts ,and, finally, to develop regional and local-scale models to fine tune the predictions made at coarse scales. In this study we conduct the first two steps, and in doing so we followed the recommendations of the IPCC experts (13) that make the plea for using a wider range of AOGCMs and emission scenarios as possible to account for variability and uncertainty in model projections. An improvement over working with narrative storylines and a limited number of AOGCM runs is to use large ensembles of model outputs constructed by varying model parameters (45, 46). These ensembles produce a range of regional changes wider than that obtained with the scenario approach used here; it also allows the calculation of probabilistic density functions that express conditional probabilities of particular outcomes given the initial assumptions and parameters entering the models.

A third step would be to develop downscaled AOGCM projections: many impacts on mountains will only be meaningfully expressed at finer resolutions, because there are difficulties in reproducing higher-order statistics and extreme values of rainfall patterns in topographically complex zones using AOGCMs. For example, the "White Paper on Mediterranean Climate Variability and Predictability" (47) discusses that regional climate models may well fill the gap between global climate models and the growing demand for climate predictions and scenarios at finer-resolution scales (48, 49, see also 50 for a brief but clear discussion on the role of RCMs in mountains). In any case, we have shown herein that the projections reported by AOGCMs and RCMs do not differ greatly. It allows politicians, planners, and researchers belonging to many areas of the Mediterranean arc, without detailed projections based on RCMs, to have broad but reliable estimations of climate change magnitudes and their uncertainties for mountainous areas.

To sum up, a significant climate change is expected for Mediterranean mountains in the 21st century. This is likely to prompt a considerable impact on the physical, biological, and social realms as illustrated by the fact that projected warming is significantly greater than that observed during the 20th century (see 51 for a global assessment on climate change on mountains). However, a degree of uncertainty still remains in climate change projections and accounting for this variability is important. Besides addressing the technical and scientific components of this variability, there is an additional challenge to communicate the significance of these uncertainties (52) to political and social agents. As stated by Ladle et al. (53), damaging simplifications of research findings "may expose environmentalists to accusations of crying wolf, and play directly into the hands of anti-environmentalists."

References and Notes

1. Barry, R.G. and Seimon, N.A. 2000. Research for mountain area development: climatic fluctuations in the mountains of the Americas and their significance. *Ambio 29*, 364–370.
2. Foster, P. 2001. The potential negative impacts of climate change on tropical montane cloud forests. *Earth-sci. Rev. 55*, 73–106.
3. Grabherr, G. 2003. Overview: alpine vegetation dynamics and climate change. In: *A Synthesis of Long-Term Studies and Observations*. Alpine Biodiversity in Europe. Nagy, L., Grabherr, G., Körner, C. and Thompson, D.B.A. (eds). Springer Verlag, Heidelberg, pp. 399–407.
4. Korner, C. 2004. Mountain biodiversity, its causes and function. *Ambio suppl. 13*, 11–17.
5. Dyurgerov, M.B. 2005. Mountain glaciers are at risk of extinction. In: *Global Change and Mountain Regions: An Overview of Current Knowledge*. Huber, U.M., Bugmann, H.K.M. and Reasoner, M.A. (ed). Springer-Verlag, Dordrecht, pp. 177–184.
6. Diaz, H.F., Grosjean, M. and Graumlich, L. Climate variability and change in high elevation regions: past, present and future. *Climate Change 59*, 1–4.

7. McNeill, J.R. 1992. *The Mountains of the Mediterranean World.* Cambridge University Press, New York.
8. Schröter, D., Cramer, W., Leemans, R., Prentice, C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., et al. Ecosystem service supply and vulnerability to global change in Europe. *Science 310*, 1333–1337.
9. Adger, N.W., Arnell, N.W. and Tompkins, E.L. 2005 Successful adaptation to climate change across scales. *Global Environ. Chang. 15*, 77–86.
10. Smagorinsky, J. 1963. General cuirculation experiments with the primitive equations. *Mon. Wea. Rev. 91*, 99–164.
11. Manabe, S. 1971. General circulation of the atmosphere. US National Report, 1967–1971, Fifteenth General Assembly, IUGG. *EOS 52*, 313–320.
12. Giorgi, T. and Mearns, L.O. 1991. Approaches to the simulation of regional climate change—a review. *Rev. Geophys. 29*, 191–216.
13. IPCC. 2000. *Special Report on Emission Scenarios.* Cambridge University Press, Cambridge.
14. IPCC. 2001. *Climate Change 2001: The Scientific Basis. Third Special Report*. Houghton, J.T, Ding, Y., Griggs, D.J., Moguer, M., van der Linden, P.J., Dai, X., Maskell, X.K. and Jonson, C.A. (eds). Cambridge University Press, New York.
15. Hulme, M. and Carter, T.R. 2000: The changing climate of Europe. In: *Assessment of the Potential Effects of Climate Change in Europe*. Parry, M.L. (ed). Report of the ACACIA Concerted Action, November 2000. UEA, Norwick, UK, 350 pp.
16. Kapos, V., Rhind, J., Edwards, M., Ravilious, C. and Price, M.F. 2000. Developing a map of the world's mountain and forests. In: *Forests in Sustainable Mountain Development: A State-of-Knowledge Report for 2000*. Price, M.F. and Butt, N. (eds). CAB International, Wallingford, UK, pp. 4–9.
17. Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M. and 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)*. Working paper 55. Report of Tyndall Centre for Climate Change Research, 30 pp.
18. Gordon, H.B. and O'Farrell, S.P. 1997. Transient climate change in the CSIRO coupled model with dynamic sea ice. *Mon. Wea. Rev. 125*, 875–907.
19. Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Duemenil, L., Esch, M., Giorgetta, M., et al. 1996. *The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present-Day Climate. Reports of the Max-Planck-Institute, Hamburg, No. 218*, 90 pp.
20. Flato, G.M. and Boer, G.J. 2001. Warming asymmetry in climate change simulations. *Geophys. Res. Lett. 28*, 195–198.
21. Gordon, C., Cooper, C., Senior, C.A., Banks, H.T., Gregory, J.M., Johns, T.C., Mitchell, J.F.B. and 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. *Clim. Dyn. 16*, 147–168.
22. Washington, W.M., Weatherly, J.W., Meehl, G.A., Semtner Jr., A.J., Bettge, T.W., Craig, A.P., Strand Jr., W.G. and Arblaster, J., et al. 2000. Parallel climate model (PCM): control and transient simulations. *Clim. Dyn. 16*, 755–774.
23. Giorgi, F. 2002. Variability and trends of sub-continental scale surface climate in the twentieth century. *Clim. Dyn. 18*, 675–691.
24. New, M., Hulme, M. and Jones, P.D. 2000. Representing twentieth-century space time climate fields. Part II: development of a 1901–1996 mean monthly terrestrial climatology. *J. Climate 13*, 2217–2238.
25. Bucher, A. and Dessens, J. 1991. Secular trends of surface temperatures at an elevated observatory in the Pyrenees. *J. Climate 4*, 859–868.
26. Maroztke, J. 2000. Abrupt climate change and thermohaline circulation: mechanisms and predictability. *Proc. Natl. Acad. Sci. USA 97*, 1347–1350.
27. Hitz, S. and Smith, J. 2004 Estimating global impacts from climate change. *Global Environ. Chang. 14*, 201–218.
28. Gritti, E.S., Smith, B. and Sykes, M.T. 2005. Vulnerability of Mediterranean Basin ecosystems to climate change and invasion by exotic plant species. *J. Biogeo. 33*, 145–157.
29. Sanz-Elorza, M, Dana, E.D., Gonzalez, A. and Sobrino, E. 2003. Changes in the high-mountain vegetation of the central Iberian peninsula as a probable sign of global warming. *Ann. Bot. 92*, 273–280.
30. Wilson, R.J., Gutierrez, D., Gutierrez, J., Martinez, D., Agudo, R. and Monserrat, V.J. 2005. Changes to the elevational limits and extent of species ranges associated with climate change. *Ecol. Letters 8*, 1138–1146.
31. Florenzano, G.T. 2004. Birds as indicators of recent environmental changes in the Apennines (Foreste Casentinesi National Park, central Italy). *Ita. J. Zoo. 71*, 317–324.
32. Stanisci, A., Pelino, G. and Blasi, C. 2005. Vascular plant diversity and climate change in the alpine belt of the central Apennines (Italy). *Biodiv. Conserv. 14*, 1301–1318.
33. Thuiller, W., Lavorel, S., Araújo, M.B., Sykes, M.T. and Prentice, C. 2005. Climate change threats to plant diversity in Europe. *Proc. Natl. Acad. Sci. USA 102*, 8245–8250.
34. Del Barrio, G., Creus, J. and Puigdefábregas, J. 1990. Thermal seasonality of the high mountain belts of the Pyrenees. *Mt. Res. Dev. 10*, 227–233.
35. López-Moreno, J.I., Nogués-Bravo, D., Chueca, J. and Julian, A. 2006. Change of topographical control on cirque glaciers extent since the little ice age. *Geophys. Res. Lett. 33*, L24505.
36. Lopez-Moreno, J.I. 2005. Recent variations of snowpack depth in the central Spanish Pyrenees. *Artic. Ant. Alp Resch. 37*, 253–260.
37. López-Moreno, J.I., Nogués-Bravo, D., Chueca, F. and Julian, A. 2006. Topographical context and glacier development. *Earth Surf. Land. Proc. 31*, 1585–1594.
38. Lasanta, T., Vicente-Serrano, S. and Cuadrat, J.M. 2005. Mountain mediterranean landscape evolution caused by the abandonment of tradicional primary activities: a study of the Spanish Central Pyrenees. *Appl. Geogr. 25*, 47–65.
39. Beguería, S., López-Moreno, J.I., Lorente, A., Seeger, M. and García-Ruiz, J.M. 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. *Ambio 32*, 283–286.
40. López-Moreno, J.I. and García-Ruiz, J.M. 2004. Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. *Int. J. Hidrol. Sci. 49*, 1–16.
41. López-Moreno, J.I., Beguería, S. and 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. *Environ. Manage. 34*, 508–515.
42. Bencherifa, A. 1990. Demography and cultural ecology of the Atlas Mountains of Morocco: Some New Hypotheses. In: *African Mountains and Highlands: Problems and Perspectives*. Messerli, B. and Hurni, H. (eds). African Mountains Association, Marceline, MD, pp. 369–377.
43. Parish, R. and Funnell, D.C. 1999. Climate change in mountain regions: some possible consequences in the Moroccan High Atlas. *Glob. Environ. Chang. 9*, 45–58.
44. Merzouk, A. and Dhman, H. 1998. Shifting land use and its implication on sediment yield in Rif mountains (Morocco). *Adv. Geoecol. 31*, 333–340.
45. Mastrandrea, M.D. and Schneider, S.H. 2004. Probabilistic integrated assessment of "dangerous" climate change. *Science 304*, 571–575.
46. Murphy, J.M., Sexton, D.M.H., Barnett, D.H., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature 430*, 768–772.
47. MedClivar Project. 2004. *White Paper on Mediterranean Climate Variability and Predictability*. Technical report. 98 pp.
48. Giorgi, F. and Mearns, L.O. 1999. Regional climate modelling revisited. *J. Geophys. Res. 104*, 6335–6352.
49. Murphy, J.M. 1999. An evaluation of statistical and dynamical techniques for downscaling local climate. *J. Climate 12*, 2256–2284.
50. Beniston M. 2003. Climatic change in mountain regions: a review of possible impacts. *Climate Change 59*, 5–31.
51. Nogués-Bravo, D., Araújo, M.B., Martinez-Rica, J.P. and Errea, M.P. 2007. Exposure of global mountain systems to climate change. *Glob. Environ. Chang. 17*, 420–428.
52. Karl, T.R. and Trenberth, K.E. 2003. Modern global climate change. *Science 302*, 1719–1723.
53. Ladle, R.J., Jepson, P., Araújo, M.B. and Whittaker, R.J. 2004. Dangers of crying wolf over risk of extinctions. *Nature 428*, 799.
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