Authors
J. López-Moreno, S. Gascoin, J. Herrero, E. A. Sproles, M. Pons, E. Alonso-González, L. Hanich, A. Boudhar, K.N. Musselman, Noah P. Molotch, J. Sickman, and J. Pomeroy

Environmental Research Letters

Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas

To cite this article: J I López-Moreno *et al* 2017 *Environ. Res. Lett.* **12** 074006

IOP Publishing *Environ. Res. Lett.* **12** (2017) 074006 https://doi.org/10.1088/1748-9326/aa70cb

Environmental Research Letters

OPEN ACCESS

RECEIVED
17 November 2016

REVISED
20 April 2017

ACCEPTED FOR PUBLICATION
3 May 2017

PUBLISHED
30 June 2017

LETTER

Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas

J I López-Moreno[1,13], **S Gascoin**[2], **J Herrero**[3], **E A Sproles**[4], **M Pons**[5], **E Alonso-González**[1], **L Hanich**[6], **A Boudhar**[7], **K N Musselman**[8], **N P Molotch**[9,10], **J Sickman**[11] **and J Pomeroy**[12]

[1] Pyrenean Institute of Ecology, CSIC, Zaragoza, Spain
[2] Centre d'Etudes Spatiales de la Biosphère, CNRS/CNES/IRD/UPS, Toulouse, France
[3] Fluvial Dynamics and Hydrology Research Group, Andalusian Institute for Earth System Research, University of Córdoba, Granada, Spain
[4] Center for Advanced Arid Zone Studies, CEAZA, Chile
[5] Observatory of Sustainability, Andorra
[6] Cadi Ayyad University, Marrakech, Morocco
[7] Sultan Moulay Slimane University, Béni-Mellal, Morocco
[8] National Center for Atmospheric Research—NCAR, Boulder, CO, United States of America
[9] Institute of Arctic and Alpine Research and Dept. of Geography, University of Colorado, Boulder, CO, United States of America
[10] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States of America
[11] Environmental Sciences, University of California, Riverside, CA, United States of America
[12] Centre for Hydrology, University of Saskatchewan, Saskatoon, Canada
[13] Author to whom any correspondence should be addressed.

E-mail: nlopez@ipe.csic.es

Keywords: snow, Mediterranean mountains, climate warming, snow simulations

Supplementary material for this article is available online

Abstract

In this study we quantified the sensitivity of snow to climate warming in selected mountain sites having a Mediterranean climate, including the Pyrenees in Spain and Andorra, the Sierra Nevada in Spain and California (USA), the Atlas in Morocco, and the Andes in Chile. Meteorological observations from high elevations were used to simulate the snow energy and mass balance (SEMB) and calculate its sensitivity to climate. Very different climate sensitivities were evident amongst the various sites. For example, reductions of 9%–19% and 6–28 days in the mean snow water equivalent (SWE) and snow duration, respectively, were found per °C increase. Simulated changes in precipitation (±20%) did not affect the sensitivities. The Andes and Atlas Mountains have a shallow and cold snowpack, and net radiation dominates the SEMB; and explains their relatively low sensitivity to climate warming. The Pyrenees and USA Sierra Nevada have a deeper and warmer snowpack, and sensible heat flux is more important in the SEMB; this explains the much greater sensitivities of these regions. Differences in sensitivity help explain why, in regions where climate models project relatively greater temperature increases and drier conditions by 2050 (such as the Spanish Sierra Nevada and the Moroccan Atlas Mountains), the decline in snow accumulation and duration is similar to other sites (such as the Pyrenees and the USA Sierra Nevada), where models project stable precipitation and more attenuated warming. The snowpack in the Andes (Chile) exhibited the lowest sensitivity to warming, and is expected to undergo only moderate change (a decrease of <12% in mean SWE, and a reduction of < 7 days in snow duration under RCP 4.5). Snow accumulation and duration in the other regions are projected to decrease substantially (a minimum of 40% in mean SWE and 15 days in snow duration) by 2050.

1. Introduction

Mediterranean mountains have been identified as places where snowmelt dominates annual runoff (Barnett *et al* 2005), and where mountain headwaters represent a large contribution to lowland river flow (Viviroli *et al* 2007). The term 'Mediterranean climate' refers to a variety of subtropical climates that are geographically distributed worldwide, including around the Mediterranean Sea, and in the western United States, north–central Chile, Australia, and South Africa. It is characterized by warm and dry summers contrasted with mild to cool winters, when most of the annual precipitation falls (López-Moreno *et al* 2011). In mountainous Mediterranean regions, a persistent winter and spring snowpack commonly develops, and this contributes to offsetting the dry summer season water deficits. In addition, when the snow melts in spring and early summer it provides some regularity to river flows, which attenuates the strong seasonal cycle of precipitation in these areas (García-Ruiz *et al* 2011). The hydrological relevance of snow is particularly evident in impounded basins, where spring snowmelt runoff fills reservoirs, and is used to meet high water demand in the summer months (particularly for agriculture, energy production, and recreational uses) when conditions are typically arid (López-Moreno *et al* 2008). Mediterranean climate regions are recognized as 'hot spots' for climate change impacts associated with increasing temperature and aridity (Milly *et al* 2005, Giorgi and Lionello, 2008). These impacts can be reflected in sharp decreases in snow accumulation and snowpack duration with associated detrimental effects on the ecosystems and economy of these regions (García-Ruiz *et al* 2011, Trujillo *et al* 2012, Bonet *et al* 2013). To understand how a snowpack might respond to climate change, it is necessary to develop credible climate projections for how the atmosphere may respond in coming decades under various greenhouse gas emission scenarios. It is also necessary to develop an understanding of the sensitivity of a snowpack to climatic change, as it has been reported to be highly variable (Pomeroy *et al* 2015, Sun *et al* 2016). Differences in sensitivity of snowpacks to climate variability and change have been related to elevation (with greater sensitivity expected in areas closer to the 0 °C isotherm during the cold season; Pierce and Cayan, 2014), slope and aspect (with greater sensitivity in highly irradiated slopes; López-Moreno *et al* 2014), and the temporal distribution of precipitation during snow-dominated seasons (Sun *et al* 2016). Less is known about how different climate conditions may affect partitioning of snow energy balance components and the snowpack characteristics (Musselman *et al* 2017); such information is central to identifying the physical drivers of differences in the sensitivity of snowpacks (Rasouli *et al* 2014 and 2015).

The hypothesis underpinning this study is that mountain areas in Mediterranean climate regions encompass sufficient climate variability to result in distinctly contrasting snow energy and mass balance (SEMB) characteristics, and that this is associated with different sensitivities to changing temperature and precipitation. To reveal these varied climate sensitivities, this study simulated the SEMB using atmospheric forcings observed in Mediterranean alpine environments world-wide.

To better compare the sensitivity of snow to climate across a wide range of site elevations and latitudes, an elevation normalization procedure was used. Sensitivity was considered in the context of expected changes in snow accumulation and duration under the climate projections of emissions scenarios corresponding to two widely used representative concentration pathways (RCPs 4.5 and 8.5) for the mid-21st century.

2. Methodology and study sites

In this study we used quality checked hourly records of temperature, precipitation, relative humidity, incoming solar radiation, and wind speed from six automatic weather stations (AWS) located in mountain areas of the Pyrenees (Spain and Andorra), the Spanish Sierra Nevada, the California Sierra Nevada (USA), the Atlas Mountains (Morocco) and the Andes (north–central Chile) (figure 1(*a*)). Elevation, aspect, wind exposure, and forest cover can be extremely variable over short distances, and this can introduce substantial spatial variability in the sensitivity of snow to climate (Rasouli *et al* 2015). Although this study did not include all Mediterranean climate mountain areas globally, and for the mountain ranges considered we did not investigate internal variability (e.g. over elevation gradients), the dataset we present broadly encompasses the contrasting climatic conditions that occur in snow-dominated areas having a Mediterranean climate.

Table 1 shows the characteristics of the meteorological stations, the length of the available records, and the mean meteorological data for the December–March (DJFM) period (June–September for Chile). The six study sites are commonly snow-covered in this period, although in some mountains, including the Pyrenees and both Sierra Nevada ranges, the duration of snow cover is normally longer. Snowpack was simulated using SNOBAL (Marks *et al* 1999), a physically-based platform implemented in the Cold Regions Hydrological Modelling platform (CRHM; Pomeroy *et al* 2007). The capacity of the model (forced using the observed meteorological data) to simulate the inter-annual variability of snow accumulation and duration at each site was evaluated (supplementary figure SF1, available at stacks.iop.org/ERL/12/074006/mmedia). Results indicate that despite obvious biases, SNOBAL provides a robust

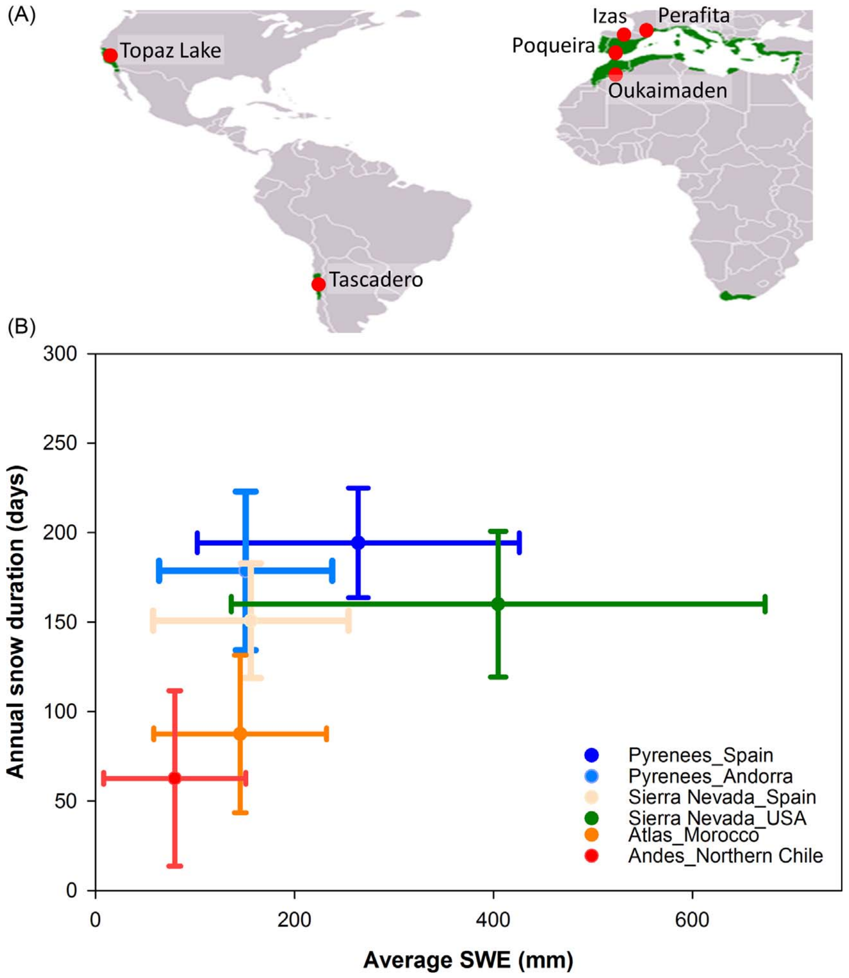

Figure 1. (*a*) Locations of the automatic weather stations. Green colour indicates the regions with Mediterranean climate. (*b*) Mean SWE and snow duration simulated for the various study sites at an elevation where the isotherm from December to March is –2 °C. Error bars indicate the 10th and 90th percentiles of interannual variability.

Table 1. The mean climatic characteristics for the period December–March (June–September for Chile). Elev. −2 °C is the elevation where the DJFM temperature is −2 °C (considering a temperature lapse rate was 0.65 °C 100 m^{-1}), RH is relative humidity, Ri is the daily incoming shortwave radiation, Ws is the wind speed, Prec. is precipitation, and % Prec. is the percentage of annual precipitation that falls between December and March.

Station	M. range	Country	Length of data	Lat.	Elev m	Elev. −2 °C	T °C	RH %	Ri W m^{-2}	Wind ms^{-1}	Prec. mm	% Prec.
Perafita	Pyrenees	Andorra	6yr	42°N	2415	2282	−3.4	60	136	3.5	396	34
Izas	Pyrenees	Spain	13yr	42°N	2056	2170	−1.3	68	121	2.7	484	30
Poqueira	S. Nevada	Spain	6yr	37°N	2500	2914	0.6	47	174	4.4	496	67
Topaz Lake	S. Nevada	USA	10yr	36°N	3220	2980	−3.6	51	157	2.3	1130	75
Oukaimaden	Atlas	Morocco	6yr	31°N	3239	3299	−1.3	50	185	2.9	280	46
Tascadero	Andes	Chile	3yr	31°S	3500	3697	−0.7	34	181	3	277	66

means simulating the interannual variability of SWE and duration of snowpack, with r^2 values always over 0.6, and a mean absolute error that rarely exceeds 15% of the observed average values. Simulations for the station of Tascadero (Northern Chile) were only available for three years. Fortunately, the three years fell within a period with a high climatic and snow variability including El Niño and La Niña years. The three years are adequately simulated but the results derived from this short period must be considered with particular caution.

Because snowpack is highly sensitive to elevation in relation to the 0 °C isotherm (Pierce and Cayan, 2014), the range of elevations (1444 m) of the AWS locations in this study limited comparability among sites. To overcome this problem, an elevational offset was calculated for each station, based on its December to March (DJFM) mean temperature. The offset was calculated using a temperature lapse rate of 0.65 °C 100 m^{-1} (Lundquist and Cayan, 2007, Schaner *et al* 2012) to equate to a common mean winter temperature of −2 °C (mean DJFM –2 °C). This way, synthetic climatology was obtained for each station that was comparable and designed to highlight differences in regional synoptic meteorology and other factors whilst holding the basic climate parameter of winter temperature the same. The elevational offset for each station was applied to its hourly forcing data in the model simulations for the whole year. Determination of the mean DJFM −2 °C isotherm relied on the fact that this value implies the smallest modification of the original records (the mean absolute difference across all sites between the observed temperature and the –2 °C DJFM isotherm is 188 m; see table 1). Moreover, at the elevation of the mean DJFM −2 °C isotherm the winter snowpack was continuous at all sites for the majority of years involved in the study; in Chile and Morocco the snowpack is ephemeral at the elevation of the mean 0 °C winter temperature isotherm. One other point is that the elevations for the normalized climates all exist in these mountain regions and so these are real locations that the meteorological station data have been extrapolated to.

Precipitation changes were assumed to be insignificant for a maximum difference of 400 m of elevational offset applied to the stations. It is recognized that precipitation changes with elevation in mountainous regions. Therefore, tests are shown in this paper to ensure that the lack of inclusion of precipitation adjustments does not affect the analysis of the sensitivity of snowpacks to climate warming. Water vapour pressure was held constant as long as it is unsaturated.

Following adjustment of the temperature data from the AWSs, the SEMB and the main characteristics of snowpacks (depth, SWE, and snow temperature) were simulated using SNOBAL, with the same module structure applied in López-Moreno *et al* (2014). CRHM simulated the meteorological and long wave radiation inputs to SNOBAL, and calculated albedo decay. Shortwave radiation was measured at each station and not adjusted. Incoming longwave radiation was estimated using the short wave radiation to calculate transmittance of the atmosphere and air temperature (Sicart *et al* 2006), and then applied to the energy balance snowmelt module. Turbulent energy transfer within Snobal is calculated with a method adapted from Brutsaert (1982) by Marks and Dozier (1992), and described in detail in Reba *et al* (2011). The method uses a system of nonlinear equations to simultaneously solve for the Obukhov stability length and the mass flux by sublimation from, or condensation to, the snow surface. Stability profile functions, necessary for the iterative solution used in the model for stable conditions, are adapted from Webb (1970) and for unstable conditions from Paulson (1970).

SNOBAL snow temperatures and turbulent transfer calculations have been evaluated extensively in various mountain snow environments from cold (Canada) to temperate climates (California and Idaho) and have been found to work extremely well without tuning (Marks *et al* 2008, Reba *et al* 2012). The sensitivity of SNOBAL model parameterizations have been evaluated by Reba *et al* (2014), confirming a low sensitivity to changes in surface roughness. Albedo was estimated using the method proposed by Gray and Landine (1987), and involved applying a value of 0.9 for fresh snow, and a linear decay for older snow. A source of uncertainty regarding snow albedo under future climates is the potential shift in the timing and magnitude of dust storms, however this is beyond the scope of this paper. Previous efforts demonstrate that SNOBAL can operate well under the current and future climates presented in this paper (Reba *et al* 2011).

Simulations were repeated for temperature increases at 1 °C intervals to a warming of 4 °C (see SF2 and Rasouli *et al* 2014 for full description of the methodology), and were undertaken on the assumption of a change of ± 20% in precipitation. The ± 20% value approximates the uncertainty of precipitation simulated in climate models for the Mediterranean region (Knutti and Sedláček 2013). Snow simulations were conducted assuming a horizontal plane for incoming radiation using the equation from Garnier and Ohmura (1970). Relative humidity was held constant to allow water vapour pressure to vary in a manner consistent with the ideal gas law (Rassouli *et al* 2014).

Finally, we simulated changes in snowpack based on the mean projected change in temperature and precipitation from December to March by the middle of the 21st century. The climate predictions were created in the framework of phase 5 of the Coupled Model Integrated Project (CMIP 5; Taylor *et al* 2012). We used two radiative forcing scenarios defined by the Representative Concentration Pathways (RCPs): 4.5 and 8.5. These correspond to the intermediate and highest level of radiative forcing for the next few decades (Meinshausen *et al* 2011). The magnitude of change by 2050 was estimated by subtracting the mean simulated values from 25 model runs for the period 2035–2065 from those for the 1980–2010 (control) period.

3. Results and discussion

Table 1 and SF3 show that despite generally having Mediterranean climates, there are marked climatic differences among the sites, which translate into major differences in snow accumulation and duration (figure 1(*b*)). Differences in air temperature are mainly driven by latitude and elevation. The Pyrenees have the two coldest sites, and the Morocco and Chile sites are the warmest. Morocco and Chile have the highest incoming solar radiation and the lowest relative humidity. The Sierra Nevada ranges in Spain and the USA have intermediate temperature and relative humidity levels.

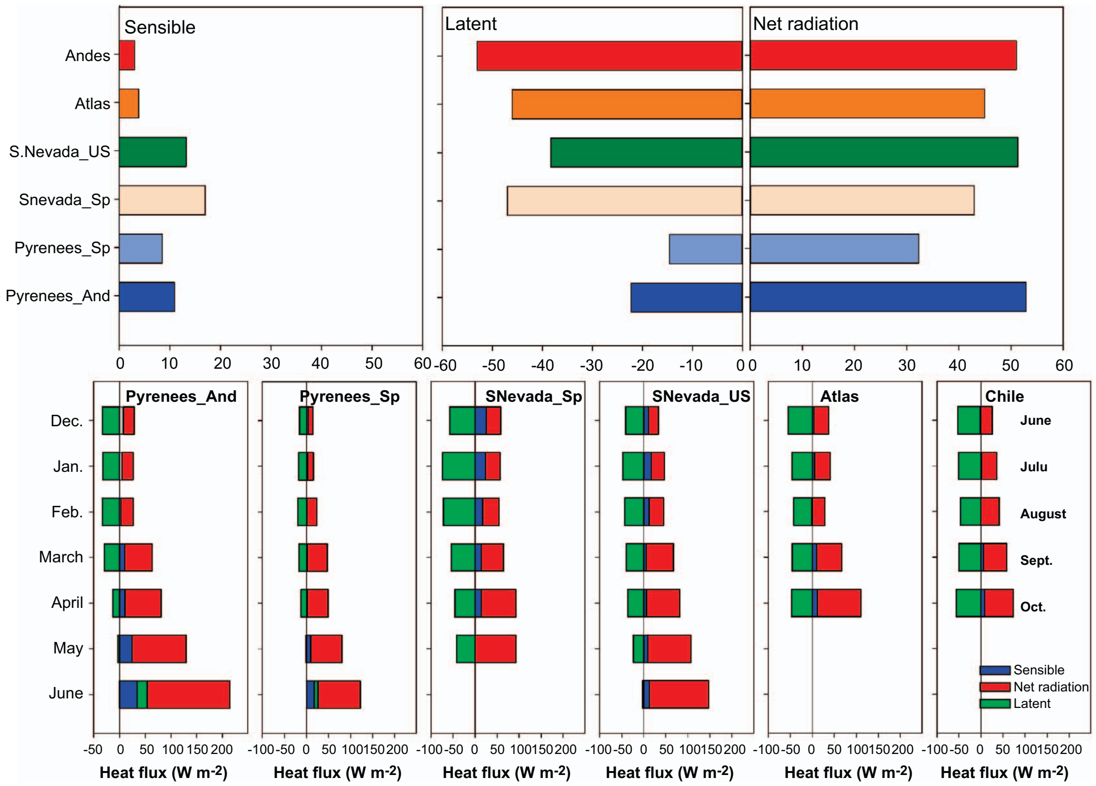

Figure 2. Simulated energy fluxes (radiation, latent and sensible heat fluxes) at the various study sites, simulated at an elevation where the mean temperature from December to March is −2 °C. The top panels show the annual average hourly fluxes, and the bottom panels show the monthly average hourly fluxes.

The USA Sierra Nevada has the highest level of winter precipitation (DJFM: 1130 mm), in contrast to other months. Other sites, including the Pyrenees, have a different seasonal distribution of precipitation, with spring snowfall being typical under current climate conditions (SF3). The seasonal climatic variability includes a moderate snowpack depth (mean SWE $>$ 190 mm) and mean snow cover duration of $>$ 170 days at the two Pyrenees sites. Very high winter precipitation in the USA Sierra Nevada results in the deepest snowpack (mean SWE, 400 mm), but because of the low level of spring precipitation and higher solar radiation, the snowpack duration (150 days) is substantially less than in the Pyrenees, and is more similar to the Spanish Sierra Nevada. As a result of low precipitation levels and high incoming solar radiation, the Atlas Mountains and the Andes have the shallowest and least persistent snowpack.

The climate differences lead to differences in the amount and duration of snow at each site, but also to marked differences in the characteristics of the SEMB (figure 2). Overall, net radiation is the most important energy flux, but it is slightly less dominant in the Spanish Pyrenees. Sensible heat fluxes are more relevant in the Spanish and USA Sierra Nevada sites, followed by those in the Pyrenees; lower levels occur at the more semiarid stations. Another important component of the SEMB is the loss of latent energy as a result of sublimation. At all sites this loss of latent energy is particularly significant during the coldest months. The largest losses of latent heat were recorded in the Andes and Spanish Sierra Nevada. At both of these sites, RH is relatively low and solar radiation is relatively high. Hence available energy at the snowpack surface is relatively high at these sites, and given the relatively dry atmosphere, this available energy is partitioned to latent heat flux; relatively high wind speeds at the Spanish Sierra Nevada site further enhanced latent heat exchange.

At the Andes and Spanish Sierra Nevada sites, sublimation represents approximately 39% and 29% of total accumulated snow, respectively (SF4); similar losses have been reported for the Spanish Sierra Nevada (Herrero and Polo, 2016). Energy losses are also very high in the Atlas Mountains, where sublimation represents 25% of total snow accumulation, consistent with Boudhar *et al* (2016) who estimate that sublimation represents 20% of total accumulation in the Atlas Mountains. In the USA Sierra Nevada the absolute level of sublimation is also very high, but the snow loss percentage is relatively low (11.5%) given the relatively high amounts of precipitation. The two Pyrenean sites have much lower losses of latent heat, and the snow loss percentage is low (10.5% and 13% at the Spanish and Andorran stations, respectively).

The results of the sensitivity analyses conducted for the six sites are shown in SF 5, and are summarized

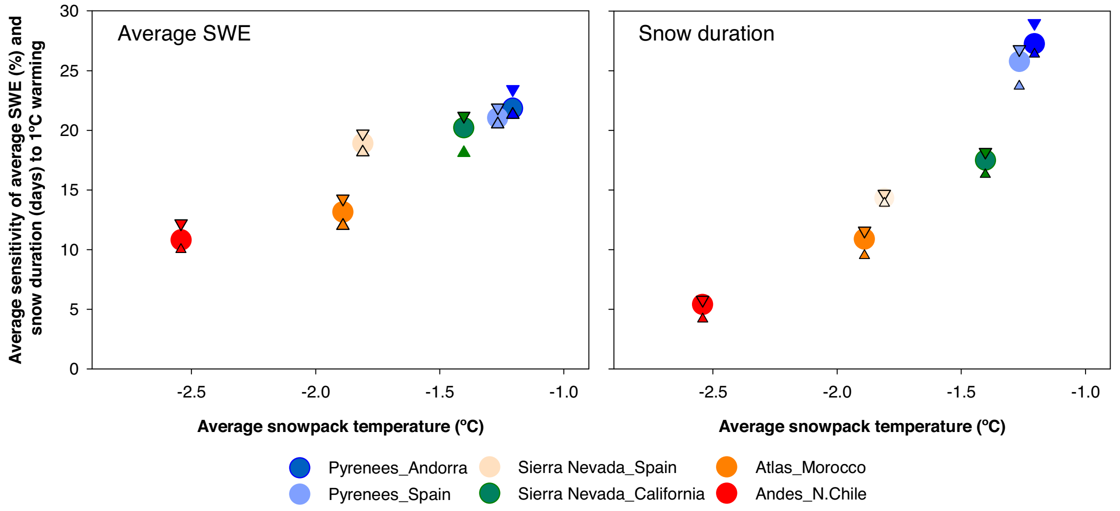

Figure 3. Percent change of the mean SWE and snow duration per °C (calculated for a temperature increase from 1 to 4 °C) versus the simulated mean snowpacks temperature. Upward and downward triangles indicate the magnitude of the sensitivity for +20% and −20% precipitation.

in figure 3. The results show that Mediterranean climate snowpacks are very sensitive to temperature increases (López-Moreno *et al* 2014), but the magnitude differed markedly among the sites. Figure SF5 also shows that a change of ±20% in precipitation markedly affects the mean SWE and the snow duration period. In general, a change of 20% in precipitation is equivalent to the effect on snow accumulation and duration of a 1 °C temperature change. Hence precipitation is an important factor in properly assessing the effect of climate warming on snowpack and snow hydrology (Irannezhad *et al* 2016). For example, it has been observed that recent warming in the California Sierra Nevada has not significantly affected the 1 April SWE, because of increased winter precipitation (Luce *et al* 2014). However, it is noteworthy that the rate of decrease in mean SWE and snow duration due to increased temperature is very similar under observed and +20% and −20% modeled precipitation (figure 3). This finding supports our assumption that not adjusting precipitation data from the AWS elevation to the elevation of the mean winter −2 °C isotherm is unlikely to have a significant impact on the sensitivities reported in this study.

Figure 3 shows large differences in mean sensitivity of snow to climate warming amongst the six sites. The mean SWE decreased by 10%–15% per °C in the Andes and Atlas Mountains, respectively, and by > 20% in the USA Sierra Nevada and the Pyrenees. Even greater differences were observed in snow duration. In the Andes the snow duration was reduced by 5.5 days per °C, whereas in the Pyrenees it was reduced by > 25 days per °C. The differing sensitivities of snowpacks appeared to be closely related to the simulated mean snowpack temperature. However, supplementary table 1 and SF 6 show that the simulated snow pack temperature was closely related to other simulated characteristics of snowpacks and several components of the snow energy balance, and also to the sensitivity of the snowpack at the various analyzed sites. Thus, a colder snowpack results from energy losses by sublimation, and where a thinner snowpack is restricted to the coldest months (Burns *et al* 2014). This effect, which was most evident in the Andes and the Atlas Mountains, is consistent with a report of the possibility of colder soils occurring in a warmer world (Groffman *et al* 2001). Conversely, the thicker snowpack in the Pyrenees and the USA Sierra Nevada leads to near-isothermal snowpack conditions. At these sites the mean snow temperature is close to 0 °C , and sensible heat flux is more important with respect to the SEMB. Hence, these sites had the highest observed sensitivity to temperature increase. In the case of the Pyrenees, the occurrence of spring precipitation at air temperatures close to the liquid/solid threshold may also explain the very high sensitivity.

It is noteworthy that sites having colder snowpacks coincided with those where radiation and latent heat flux have a major influence on the SEMB. This could explain the lower sensitivity of the snowpacks in Chile and Morocco. The Spanish Sierra Nevada exhibited intermediate sensitivity of the snow temperature to climate warming. In a glaciological study in Tibetan Plateau, Huitjes (2014) also found a much higher climate sensitivity of glaciers in more temperate and wetter climate locations compared to dryer ones.

Figure 4 clearly illustrates the differing sensitivities of the mean SWE and snow duration to various climate projections for the future. All climate models (CMIP 5) project a temperature increase of 1.2 °C –1.6 °C and 1.6 °C–2.3 °C for RCPs 4.5 and 8.5, respectively, and relatively stable winter precipitation. Exceptions are the Spanish Sierra Nevada and the Atlas Mountains, where precipitation decreases of 11–16% (RCP 4.5) and 17%–23% (RCP 8.5) are projected,

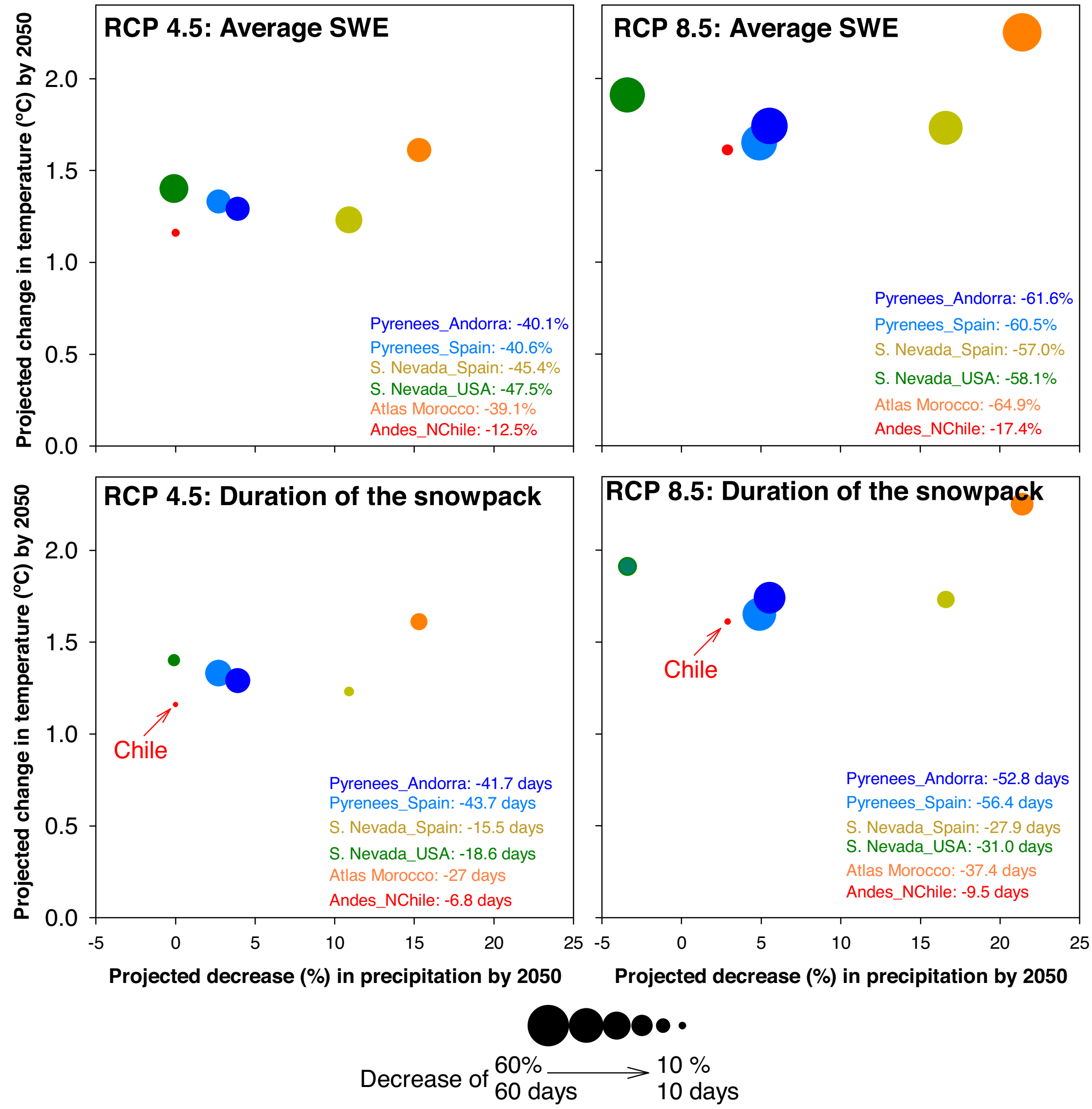

Figure 4. Expected change in mean SWE (%, upper panels) and duration of the snowpacks (days, lower panels) in relation to expected changes in temperature and precipitation (December–March) projected for 2050 (intermodal mean for 2035–2065 compared with 1970–2000), based on RCPs 4.5 (left panels) and 8.5 (right panels). The location of the circles informs about the average change projected for temperature and precipitation. The size of the circles inform about the magnitude of the decrease of average SWE and duration of the snowpack.

respectively. Despite projected warmer and drier conditions, the snow of the Spanish Sierra Nevada and the Atlas Mountains are less sensitive to projected climate change and show a smaller decrease in mean SWE and snow duration as compared to the more sensitive snow of the Pyrenees.

In the semiarid Andes the increase in air temperature is expected to be similar to that in the Pyrenees and Sierra Nevada (Spain) and precipitation is expected to remain relatively unchanged. The latter, combined with the lowest sensitivity of the snowpack among all study sites, attenuates the snow response to climate change, with a decrease of $< 20\%$ in SWE and 10 days in snow duration, even under the highest greenhouse gas emissions scenario (RCP 8.5). With the exception of Chile, the combination of climate projections and sensitivity of the snowpack indicate a dramatic decrease in the mean SWE by 2050, ranging from −39.1 to 47.5% and 57 to 64.9% for RCPs 4.5 and 8.5, respectively. However, the reduction in the duration of snow cover is projected to be much more variable among the sites, ranging from 15.5 to 43.7 days and 27.9 to 56.4 days for RCPs 4.5 and 8.5, respectively. Overall, the snowpack in the Pyrenees is expected to be the most impacted by climate change.

The different sensitivities of snow to projected climate change suggest that the study locations expected to have relatively greater temperature increases may not have the greatest loss of snowpack or greatest reduction in snow duration. Thus, intermediate projections of warming and decreasing precipitation for the Pyrenees make it one of the most affected mountain areas in the study. This area showed a similar or greater decrease in mean SWE and snow duration than the Atlas Mountains and the Spanish Sierra Nevada, where the projected warming and drying is much greater. The snowpack in the Andes in central–northern Chile, where moderate warming, stationary precipitation, and the lowest sensitivity is projected, is expected to be the least impacted area compared with other study sites. These other mountain areas are expected to be subject to major reductions in the mean winter SWE and snow duration by the middle of the 21st century, especially under RCP 8.5.

The results presented in this study are obviously subjected to a number of inherent uncertainties that affects the whole chain of this methodological approach. Data collected in high mountain environments, the simulation of the energy and mass balance with limited observations, the use of limited records (as is the case of Tascadero), and the linkage of all this information with climate projections for future scenarios introduce obvious uncertainties that are difficult to quantify precisely. However, we are confident that we have used the best meteorological forcing available for Mediterranean mountains and that SNOBAL can operate well under the conditions of current and future climates presented in this paper, as has been shown in previous research (Marks *et al* 2008, Fang *et al* 2013). This statement is corroborated by the relatively low errors obtained in this study across a broad range of climatic conditions. Thus, despite the aforementioned uncertainties, the results of this study confirm that (i) variations in the SEMB, and associated snow properties, drive the different snowpack sensitivities to climate warming; and (ii) the impacts on the snowpack reported in this study may severely affect the total amount and seasonality of available water for environmental flows and various economic activities (Mankin *et al* 2015)

This study provides a framework for analyzing snowpack sensitivities to climate warming in Mediterranean mountain areas, and for evaluating the downstream socio-economic impacts resulting from changes in water variability and security. For example, a reduction in the snowpack in California during 2014 led to drought conditions that cost an estimated $2.7 billion (Howitt *et al* 2014). While water does not serve as the direct cause of armed conflict, it can serve as an exacerbating factor within and among countries (Wolf, 2007). The methods and analysis we present identify the physical and environmental characteristics that negatively impact the mountain snowpacks in Mediterranean climates, and potentially increase water resource variability.

4. Conclusions

Comprehensive observational records from AWSs were used in a physically-based snow model to illustrate that different climate conditions can lead to contrasting snow characteristics, snow properties, and partitioning of the SEMB. These differences lead to very contrasting sensitivities of snow accumulation and duration to climate, even within mountain ranges classified as having the same climate type. The six sites showed substantial differences in snowpack duration and thickness that, combined with different partitioning of the SEMB components, will lead to very different sensitivities of the snowpack to climate warming. Data from the AWS in the most arid study sites indicate that a thinner snowpack and high energy losses through sublimation lead to the coldest mean snow temperatures. In such areas, a cold snowpack in combination with small contributions of energy from sensible heat leads to lowered sensitivity to climate warming. Conversely, the Pyrenees have a moderately deep and seasonally persistent snowpack, and in this area small losses of energy through sublimation and a large contribution of sensible heat flux to the energy balance explain its high degree of sensitivity to temperature increase. The Spanish and USA Sierra Nevada ranges have conditions that are intermediate between the Pyrenees and the most arid sites. The seasonal distribution of precipitation during the snow season has also been identified as a potential driver of differences in snow sensitivity among the studied mountain areas. Given the high seasonality of precipitation and semi-arid nature of Mediterranean climates, the results presented here may have significant impacts on water availability in these heavily populated and highly productive agro-ecosystems.

Acknowledgments

This study was funded by the research projects CGL2014-52599-P ‘Estudio del manto de nieve en la montaña española y su respuesta a la variabilidad y cambio climatico’ (Ministry of Economy and Development, MINECO), I-link+ project (Spanish Research Council, CSIC) ‘Development of methods for monitoring and simulating snow cover and water resources and their response to climate change in semiarid Northern Chile’, and CLIMPY: ‘Characterization of the evolution of climate and provision of information for adaptation in the Pyrenees’ (FEDER-POCTEFA). It is a contribution to the International Network for Alpine Research Catchment Hydrology (INARCH) under the Global Energy and Water Exchanges (GEWEX) Project, which aims to compare snow regimes in mountains around the world

References

Barnett T P, Adam J C and Lettenmaier D P 2005 Potential impacts of a warming climate on water availability in snow-dominated regions *Nature* **438** 303–9

Bonet F J, Millares A and Herrero J 2013 Snowpack as a key element in mountain ecosystem services: some clues for designing useful monitoring programs *Earth Observation of Ecosystem Services* (Boca Raton, FL: CRC Press) pp 329

Boudhar A, Boulet G, Hanich L, Sicart J E and Chehbouni A 2016 Energy fluxes and melt rate of a seasonal snow cover in the Moroccan High Atlas *Hydrol. Sci. J.* **61** 931–43

Burns S P, Molotch N P, Williams M W, Knowles J F, Seok B, Monson R K, Turnipseed A A and Blanken P D 2014 Snow temperature changes within a seasonal snowpack and their relationship to turbulent fluxes of sensible and latent heat *J. Hydrol.* **15** 117–42

Brutsaert W 1982 *Evaporation in to the Atmosphere: Theory, History, and Applications* ed D Reidel (Norwell, MA: Springer) pp 316

Dequé M *et al* 2005 Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from prudence results *Clim. Dynam.* **25** 653–70

Fang X, Pomeroy J W, Ellis C R, MacDonald M K, DeBeer C M and Brown T 2013 Multi-variable evaluation of hydrological model predictions for a headwater basin in the Canadian Rocky Mountains *Hydrol. Earth Syst. Sci.* **17** 1635–59

Garnier B J and Ohmura A 1970 The evaluation of surface variations in solar radiation income *Sol. Energy* **13** 21–34

García-Ruiz J M, López-Moreno J I, Serrano-Vicente S M, Beguería S and Lasanta T 2011 Mediterranean water resources in a global change scenario *Earth. Sci. Rev.* **105** 121–39

Giorgi F and Lionello P 2008 Climate change projections for the Mediterranean region *Glob. Planet. Change* **63** 90–104

Gray D M and Landine P G 1987 Albedo model for shallow prairie snowcovers *Can. J. Earth Sci.* **24** 1760–68

Groffman P M, Driscoll C T, Fahey T J, Hardy J P, Fitzhugh R D and Tierney G L 2001 Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem *Biogeochemistry* **56** 135–50

Herrero J and Polo M J 2016 Evaposublimation from the snow in the Mediterranean mountains of Sierra Nevada (Spain) *The Cryosphere* **10** 2981–98

Howitt R, Medellín-Azuara J, MacEwan D, Lund J and Sumner D 2014 Economic analysis of the 2014 drought for California agriculture (Davis, CA: Center for Watershed Sciences, University of California, Davis)

Huitjes E 2014 Energy and mass balance modelling for glaciers on the Tibetan Plateau: Extension, validation and application of a coupled snow and energy balance model *PhD dissertation* RWTH Aachen University (http://publications.rwth-aachen.de/record/459462/files/5239.pdf?version=2) 244 pp

Irannezhad M, Ronkanen A K and Kløve B 2016 Wintertime climate factors controlling snow resource decline in Finland *Int. J. Climatol.* **36** 110–31

Knutti R and Sedláček J 2013 Robustness and uncertainties in the new CMIP5 climate model projections *Nat. Clim. Change* **3** 369–73

López-Moreno J I, García-Ruiz J M and Beniston M 2008 Environmental change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains *Glob. Planet. Change* **66** 300–12

López-Moreno J I, Revuelto J, Gilaberte M, Morán-Tejeda E, Pons M, Jover E, Esteban P, Garcia C and Pomeroy J 2014 The effect of aspect on the response of snowpack to climate warming in the Pyrenees *Theor. Appl. Climatol.* **117** 207–19

López-Moreno J I, Vicente-Serrano S M, Morán-Tejeda E, Lorenzo J, Kenawy A and Beniston M 2011 NAO effects on combined temperature and precipitation winter modes in the Mediterranean mountains: observed relationships and projections for the 21st century *Glob. Planet. Change* **77** 72–66

Luce C H, Lopez-Burgos V and Holden Z 2014 Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models *Water Resour. Res.* **50** 9447–62

Lundquist J D and Cayan D R 2007 Surface temperature patterns in complex terrain: daily variations and long-term change in the central Sierra Nevada, California *J. Geophys. Res.* **112** D11124

Mankin J S, Viviroli D, Singh D, Hoekstra A Y and Diffenbaugh N S 2015 The potential for snow to supply human water demand in the present and future *Environ. Res. Lett.* **10** 114016

Marks D, Domingo J, Susong D, Link T and Garen D 1999 A spatially distributed energy balance snowmelt model for application in mountainous basins *Hydrol. Process.* **13** 1935–59

Marks D and Dozier J 1992 Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance *Water Resour. Res.* **28** 3043–54

Marks D, Reba M, Pomeroy J, Link T, Winstral A, Flerchinger G and Elder K 2008 Comparing simulated and measured sensible and latent heat fluxes over snow under a pine canopy to improve an energy balance snowmelt model *J. Hydrometeorology* **9** 1506–22

Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extension from 1765 to 2300 *Clim. Change* **109** 213–41

Milly P C D, Dunne K A and Vecchia A V 2005 Global pattern of trends in streamflow and water availability in a changing climate *Nature* **438** 347–50

Musselman K N, Clark M P, Liu C, Ikeda K and Rasmussen R 2017 Slower snowmelt in a warmer world *Nat. Clim. Change* **7** 214–19

Paulson C A 1970 The mathematical representation of wind speed and temperature profiles in the atmospheric surface layer *J. Appl. Meteorol.* **9** 857–61

Pierce D W and Cayan D R 2014 The uneven response of different snow measures to human-induced climate warming *J. Clim.* **26** 4148–67

Pomeroy J W, Gray D M, Hedstrom N R, Quinton W L, Granger R J and Carey S K 2007 The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence *Hydrol. Process.* **21** 2650–67

Pomeroy J W, Bernhardt M and Marks D 2015 Water resources: research network to track alpine water *Nature* **521** 32

Rasouli K, Pomeroy J W, Janowicz J R, Carey S K and Williams T J 2014 Hydrological sensitivity of a northern mountain basin to climate change *Hydrol. Process.* **28** 4191–4208

Rasouli K, Pomeroy J W and Marks D G 2015 Snowpack sensitivity to perturbed climate in a cool mid-latitude mountain catchment *Hydrol. Process.* **29** 3925–40

Reba M L, Marks D, Winstral A, Link T E and Kumar M 2011 Sensitivity of the snow cover energetics in a mountain basin to variations in climate *Hydrol. Process.* **25** 3312–21

Reba M L, Pomeroy J, Marks D and Link T E 2012 Estimating surface sublimation losses from snowpacks in a mountain catchment using eddy covariance and turbulent transfer calculations *Hydrol. Process.* **26** 3699–3711

Reba M L, Marks D, Link T E, Pomeroy J and Winstral A 2014 Sensitivity of model parameterizations for simulated latent heat flux at the snow surface for complex mountain sites *Hydrol. Process.* **28** 868–81

Schaner N, Voisin N, Nijssen B and Lettenmaier D P 2012 The contribution of glacier melt to streamflow *Environ. Res. Lett.* **7** 034029

Sicart J E, Pomeroy J W, Essery R L H and Bewley D 2006 Incoming longwave radiation to melting snow: observations, sensitivity and estimation in northern environments *Hydrol. Process.* **20** 3697–3708

Sun F, Hall A, Schwartz M, Walton D B and Berg N 2016 Twenty-first-century snowfall and snowpack changes over the southern California mountains *J. Clim.* **29** 91–110

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Trujillo E, Molotch N P, Goulden M L, Kelly A E and Bales R C 2012 Elevation-dependent influence of snow accumulation on forest greening *Nat. Geosci.* **5** 705–9

Viviroli D, Dürr H H, Messerli B, Meybeck M and Weingartner R 2007 Mountains of the world, water towers for humanity: typology, mapping, and global significance *Water Resour. Res.* **43** W07447

Webb E K 1970 Profile relationships: the log-linear range and extension to strong stability *Q. J. R. Meteorol. Soc.* **96** 67–90

Wolf A T 2007 Shared waters: conflict and cooperation *Annu. Rev. Environ. Resour.* **32** 241–69