Climatic Change (2015) 131:591–605
DOI 10.1007/s10584-015-1400-8

The vulnerability of Pyrenean ski resorts to climate-induced changes in the snowpack

Marc Pons[1,3] **· Juan Ignacio López-Moreno**[2] **·**
Martí Rosas-Casals[3] **· Èric Jover**[1]

Received: 7 August 2014 / Accepted: 23 March 2015 / Published online: 6 May 2015

Abstract Winter tourism is the main source of income and the driving force of local development in many mountain areas. However, in recent years, the industry has been identified as being extremely vulnerable to future climate change. Although the Pyrenees has the largest ski area in Europe after the Alps, there are few detailed climate change vulnerability assessments on the ski resorts based in this region. This paper analyzes the vulnerability of the Pyrenean ski resorts to projected changes in the snowpack under various future climate scenarios. In addition, the study analyzes the sustainability of the snowmaking systems to offset the climate variability of natural snow cover. On average, the study predicts a shorter ski-season length, especially in low-altitude ski resorts in a moderate climate change scenario and for all ski resorts in a more intensive climate change scenario. However, a significant regional variability has been identified for the projected impacts at very short geographical distances within the studied area. Moreover, this paper shows that snowmaking cannot completely solve the problem for all ski resorts in the Pyrenees, as the measure can only act as a robust adaptation strategy in the region provided climate change is limited to +2 °C snowmaking.

1 Introduction

In recent decades, a significant increase in temperature has been detected in most mountain regions around the world, accompanied by a shift towards earlier snowpack melt and declining

Electronic supplementary material The online version of this article (doi:10.1007/s10584-015-1400-8) contains supplementary material, which is available to authorized users.

✉ Marc Pons
mpons@obsa.ad

[1] Sustainability Observatory of Andorra (OBSA), Pl. Germandat 7, Sant Julià de Lòria AD600, Andorra

[2] Pyrenean Institute of Ecology (CSIC), Av. Montañana 1005, Zaragoza 50059, Spain

[3] Sustainability Measurement and Modeling Lab (SUMMLab), Universitat Politècnica de Catalunya (UPC), EET, 08222 Barcelona, Spain

snow accumulation (Mote 2003; Barnett et al. 2005; Hantel and Hirtl-Wielke 2007; De Jong et al. 2009; Minder 2010). This change in snowpack dynamics results from snow sensitivity to temperature increase, causing a decreasing proportion of snowfall relative to precipitation, and an increase in available energy for snowmelt (Rood et al. 2008). Thus, a +1 °C change was reported to reduce accumulated snow by 20 % and shorten the snow season in the Pyrenees (López-Moreno et al. 2013a, b). Despite high uncertainties and a large regional variability, climate models project that the temperature will continue to increase in the coming decades (Ganguly et al. 2009). It is expected that mountain areas will be particularly affected by high rates of warming (Nogués-Bravo et al. 2007; Minder 2010; Gobiet et al. 2014), with the consequent impact on the accumulation and duration of mountain snowpacks (Adam et al. 2009; Hamlet 2011; López-Moreno et al. 2013a, b). Many research efforts have been directed at assessing what the environmental and socioeconomic effects of a thinner snowpack with a shorter duration might be, including those effects on water resource availability (Barnett et al. 2005; Adam et al. 2009), the ecology of affected areas (Tague and Dugger 2010; Trujillo et al. 2012), hydropower production (Finger et al. 2012), and ski resort viability (Abegg et al. 2007; Scott et al. 2012; Gilaberte et al. 2015). Although climate and weather are only two of the many factors affecting winter tourism, changes on the seasonal nature and availability of snow may have a significant socioeconomic impact that results in a decrease in the viability and sustainability of winter activities, such as the ski industry (Saurí and Llurdés 2010; Scott et al. 2012).

In the late 1980s and 1990s, following a succession of winters with poor snow conditions, the first academic studies emerged that dealt with the impact of climate change on the ski industry. Since then, the principal winter tourism regions of the world have been analyzed, including the European Alps (Breiling and Charamza 1999; Elsasser and Bürki 2002; König and Abegg 1997; Steiger 2010, 2012; Steiger and Abegg 2013; Steiger and Mayer 2008; Uhlmann et al. 2009; Endler and Matzarakis 2011), Canada (Scott et al. 2003, 2006, 2007), USA (Dawson and Scott 2007, 2010; Dawson et al. 2009; Nolin and Daly 2006; Scott et al. 2008), Sweden (Moen and Fredman 2007), Australia (Hennessy et al. 2003, 2008; Bicknell and McManus 2006), Japan (Fukushima et al. 2003), or New Zealand (Hendrikx et al. 2013). Some of these studies primarily focus on the supply-side impacts (ski operations), model simply natural snow conditions at ski resorts (Uhlmann et al. 2009), or apply indicators that are not relevant to ski-area operations, such as "snow cover," defined as 2.5 cm of snow (Lamothe and Périard 1988), when in fact ski operators require 30–100 cm of snow to open a ski run. With the exception of a few studies that use statistical relationships between snow depth and other climatological parameters (Moen and Fredmand 2007), most of these studies base their estimations on physical snow models. One of the major limitations to these statistical model-based studies is they omit the effect of snowmaking on the future natural snowpack, as well as the effect of factors such as rain or warm winter days that can affect the quality of snow. This limitation, found not only in statistical models but also in many other studies using physical snow models, is the main drawback in most of the previous literature assessing the vulnerability of ski resorts (Scott et al. 2012; Gilaberte et al. 2015). This is a key point as nowadays snowmaking is responsible for covering huge areas of the ski resorts and the percentage of snow-machine-covered runs increases every year (Steiger and Mayer 2008). Snowmaking is currently the main adaptation strategy used to offset the natural variability of snow. It helps to guarantee enough snow depth, scheduled openings, and stable revenues, but also represents a commercial and image strategy to extend the season in order to increase revenues (Steiger and Mayer 2008). Over the last few decades, ski resorts across the world have invested considerably in snow-production systems and the Pyrenean ski resorts are no exception to this global trend

(Saurí and Llurdés 2010). The studies discussing this issue (Scott et al. 2003, 2007, 2008; Scott 2011; Hennessy et al. 2008; Steiger 2010, 2011) found that the impacts of climate change on the various regions analyzed were lower than the impacts reported in previous studies that considered only natural snow. Finally, an alternative approach to the statistical and physical models in analyzing the climate change impacts on the ski industry is the analog approach. Temporal analogs use past and present experiences and responses to climatic variability, change, and extremes to provide insight into vulnerability to possible future climate change (Ford et al. 2010). So far, this approach has only been applied in a few studies in North America (Scott et al. 2006; Dawson et al. 2009) and one in the Austrian region of Tyrol (Steiger 2011).

Despite the heterogeneity of approaches, most of these studies are congruent in their results, indicating that climate change will lead to a reduction in ski-season length, a loss of skiable areas, and a drop in visitors, mainly in low-altitude and low-latitude ski resorts.

The Pyrenees is a 450-km-long mountain range comprising the northern part of Spain, the southern part of France, and Andorra (Fig. 1). Altitude ranges from 300 m to over 3000 m. The climate of the Pyrenees is subject to an eastward transition from Atlantic to Mediterranean conditions. Moreover, its macro relief introduces a significant variability in the distribution of precipitation and temperature. The Pyrenees is the most important winter tourism region in Europe after the Alps (Vanat 2014). Alpine skiing is the most important winter sport in this region in terms of visitors and revenues. Encompassing 49 alpine ski resorts, the region receives approximately 11 million skiers a year (average for the seasons 2009–2010 to 2012–2013 in Pons et al. 2014) (Fig. 1). The elevation of the Pyrenean ski resorts ranges from 1350 to 2700 m with a mean elevation of approximately 1950 m.

The aim of this paper is to analyze the vulnerability of the Pyrenean ski resorts to projected changes in the snowpack under various future climate scenarios. By means of a physical snow model, the changes in the natural snowpack are projected for each ski resort in two different

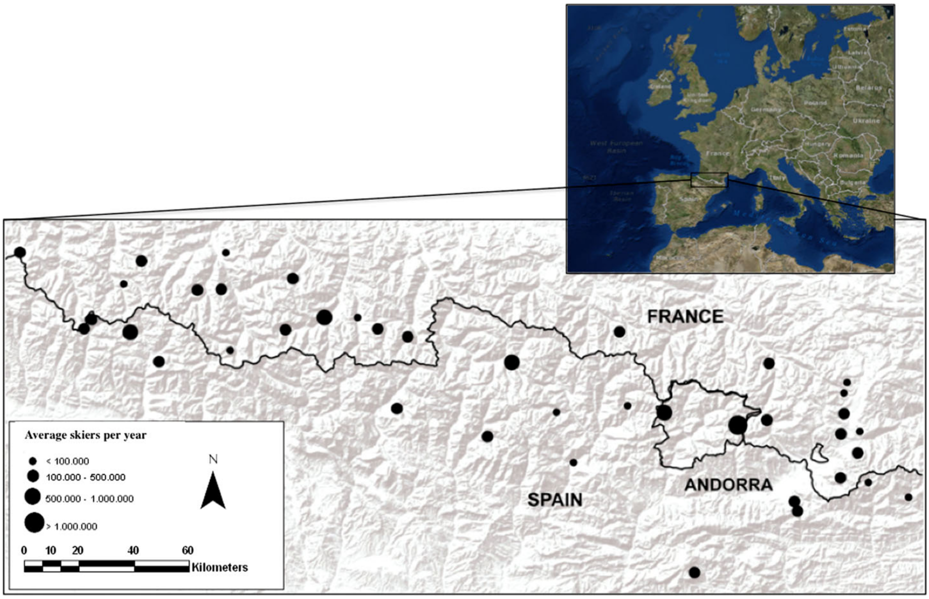

Fig. 1 Area of study and location of the ski resorts. Size of the *bullets* represents the average skier attendance at each ski resort from 2009–2010 to 2012–2013

future scenarios. Subsequently, the changes in the ski-season length of the various Pyrenean ski resorts are projected. Finally, the capacity to produce snow under these two future scenarios is assessed to analyze the suitability of snowmaking to offset climate variability of natural snow cover.

2 Data and methods

The study uses regional climate change projections in order to simulate the future natural snowpack in the various ski resorts of the Pyrenees. A snowmaking module simulating the effect of snow-production systems has been included in order to analyze the effect of these systems to enhance natural snow depth. A conceptual map with the main components of the model is shown in Fig. 2. Data from the smallest ski resorts of the Pyrenees (less than a couple of runs, often presented as a complementary activity to a hotel, or a Nordic ski resort) was not available. Only 41 of the total 49 ski resorts were hence taken in this study, representing more than 92 % of the total skiers in the region (DSF 2012; Botti et al. 2013; ATUDEM 2013; SkiAndorra 2013).

In order to estimate future natural snow conditions at each ski resort, the model uses the regional projections of the daily snowpack in the Pyrenees during the twenty-first century of López-Moreno et al. (2009). In the study conducted by López-Moreno et al. (2009), the seasonal evolution of snowpack was simulated at 20 individual points across the entire Pyrenees, each of them representing the average conditions over a surface area typical of a regional climate model (RCM) employed during the EU PRUDENCE project, with a resolution of 50 km^2 (Christensen et al. 2002). The snow depth and the snow duration were simulated by running GRound ENergy Balance for NaturaL Surfaces (GRENBLS), a surface energy balance model (Keller and Goyette 2005), with climatic inputs provided by the HIRH AM regional climate model (Christensen et al. 1998). Surface energy balance models (SEBM) for snow simulate the evolution of the snowpack based on the thermal fluxes affecting the snow. GRENBLS is a single-layer physically based model driven by hourly input data of air temperature, dew-point temperature, anemometer-level wind velocity, precipitation, surface

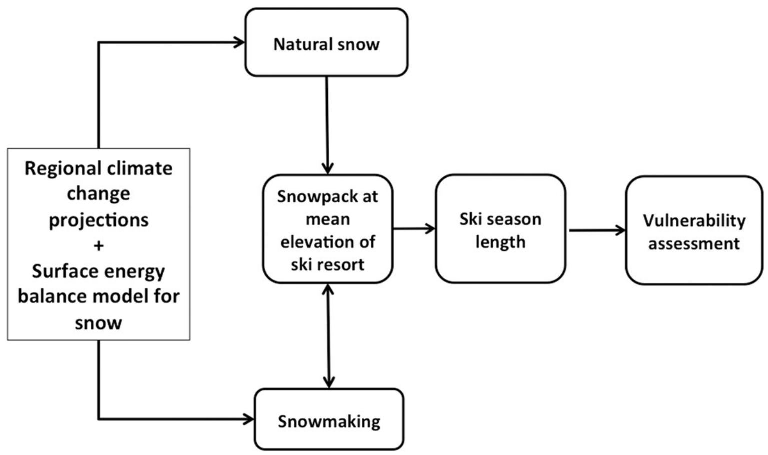

Fig. 2 Conceptual map of the model linking climate change projections of future changes in the snowpack with the vulnerability of the Pyrenean ski resorts

pressure, and incident solar radiation. As GRENBLS employs hourly data and RCMs usually provide outputs on a daily basis, these variables were disaggregated into hourly series following the procedures of Jansson and Karlberg (2004). The model computed the radiative fluxes from cloudiness data and the surface turbulent latent and sensible heat fluxes. The bulk heat and moisture transfer coefficients were parameterized according to Benoît (1977) based on the Monin–Obukov similarity theory. Surface temperature, soil moisture, and snow mass are prognostic variables. The energy budget also considered the energy change associated with the melting of frozen soil moisture and snow. The temperature of the snowpack was computed via heat storage using a force-restore method (McFarlane et al. 1992). Precipitation is considered as solid if air temperature is less than that of the triple point of water. Liquid precipitation on a snowpack induces snowmelt, and the melt water enters the soil directly in liquid form. Snow was modeled as an evolving one-layer pack characterized by temperature T_{snow} (K), mass M_{snow} (kg/m^2), and density q_{snow} (kg/m^3). The surface energy budget was computed over the snow cover at each model time step. The radiative and turbulent fluxes were computed first, followed by heat storage in the snowpack; if the latter was positive and the snow temperature was below the melting point, the excess energy was first used to raise the temperature of the pack. Once the temperature reaches the melting point, any additional excess energy is used to melt the snow. The age effect of the snow on snow density was adopted following Verseghy (1991). The snow density of the bulk snow layer increases exponentially over time from the fresh-fallen snow value, $q_{\text{snow,min}}=100$ kg/m^3, to a maximum of $q_{\text{snow,max}}=$ 300 kg/m^3. In a similar manner, changes in snow albedo that accompany snow aging were parameterized as a time-decay function from an initial fresh snow albedo of 0.80. GRENBLS also incorporates total cloudiness as an input parameter. The model was run for a control period (1961–1990) and for two future emissions scenarios, the IPCC Special Report on Emissions Scenarios (SRES) A2 and B2 (IPCC 2007), and for various altitudinal levels, 1500, 2000, 2500, and 3000 m. Outputs were snow water equivalent (SWE) and snow depth series at hourly intervals at 20 points of the Pyrenees and at 4 different altitudinal levels (1500, 2000, 2500, and 3000 m). Between these altitudinal levels, the snow depth was interpolated in order to simulate the snowpack every 150 m. The model was calibrated with a control period, and its performance was validated, finding good agreement in the overall snow depth and duration between the observed and simulated snowpack in the Pyrenees (see detail of validation in López-Moreno et al. 2009). Only Formigal (central-western part of the Pyrenees) presented significantly different behavior to the simulated data. In this case, the snowpack was modeled using the Cold Regions Hydrological Model (CRHM) (Pomeroy et al. 2007) with historical data from the nearest meteorological station to the ski resort, Izas (López-Moreno et al. 2013a, b). The CRHM platform uses a modular modeling object-oriented structure to simulate a comprehensive range of hydrological phenomena in mountainous and cold regions (including blowing snow, intercepted snow, energy balance snowmelt, infiltration to frozen soils, etc.).

The 30-cm threshold is commonly used as the average minimum snow depth to operate a ski resort (Witmer 1986; Abegg et al. 2007; Scott et al. 2008; Steiger 2010). Thus, for each ski resort, season lengths have been analyzed by taking into account the number of days during an average winter season in which this lower boundary is reached. The ski-season length has been calculated by applying this 30-cm threshold to the natural snowpack projections obtained from the snow model at the mean elevation of each ski resort. This elevation is used as an indicator of the average snowpack available at each ski resort (Abegg et al. 2007; Scott et al. 2003; Scott and McBoyle 2007; Steiger 2010).

The model includes a snowmaking module in order to simulate the effect of snowmaking systems in enhancing the snowpack in order to achieve a more realistic projection of the future ski-season length. Moreover, by including the capacity to produce snow in future climate change scenarios, the suitability and the sustainability of this adaptation strategy can also be assessed. In this model, only snowmaking to ensure the minimum snow conditions has been simulated. Following the experience of technical staff in ski resorts, a daily minimum temperature threshold of −2 °C has been used as a proxy to compute the potential snowmaking days during a typical winter season. In line with previous studies (Scott el al. 2008; Steiger, 2011), it is assumed that during these potential snowmaking days, a maximum of 10 cm per day can be produced to reach the 30-cm threshold. Thus, the natural snow depth is complemented with snowmaking according to these criteria. The resulting season length will depend on the natural snowpack available and the potential snow produced by these systems. Once the season length of each resort has been projected based on the natural snow availability and snowmaking production, the season lengths have been analyzed by taking into account the number of days during an average winter season for each scenario. Using the “100-day” criterion (Abegg et al. 2007; Dawson and Scott 2007, 2010; Scott et al. 2003; Scott and McBoyle 2007; Steiger 2010; Witmer 1986), the ski resorts reaching the 30-cm threshold during at least 100 days per winter season are considered as being “reliable” and any that do not are considered “unreliable.”

3 Results

3.1 Projected changes in the snowpack in Pyrenean ski resorts

The model simulations project that the snowpack in the Pyrenees will be strongly affected by projected climate changes, with a marked decrease in snow depth and duration of the snowpack (Fig. 3). Various greenhouse gas emission scenarios (SRES) lead to significant differences in the severity of expected changes in the snowpack, with these differences being twice as pronounced under scenario A2 compared to B2. Noticeable spatial differences in the magnitude of simulated changes in snowpack have been detected. The snowpack in the central and eastern areas of the Spanish Pyrenees is clearly the most affected by climate change. The impact of climate change on the snowpack is highly sensitive to altitudinal gradient. A decrease in snow depth at 3000 m is just 25 % of that simulated at 1500 m. In the highest sectors under SRES A2 and B2, snow depth is predicted to decrease by 11 and 5 %, respectively. In the lowest sectors, snow depth is predicted to decrease by up to 70 and 32 %, respectively, and the duration of the snowpack by 78 and 44 %.

Three different scenarios have been evaluated in order to analyze the vulnerability of the Pyrenean ski resorts to projected changes in the future snowpack. The first scenario simulates the current average winter season, while the other two simulate future snow depth, assuming a 2 °C increase in the winter mean temperature (equivalent to SRES B2 at the end of the twenty-first century) as a moderate climate change scenario, and a 4 °C increase (equivalent to SRES A2 at the end of 21st century) as a strong climate change scenario (López-Moreno et al. 2008). These two scenarios consider future changes in air temperatures as well as changes in precipitation, wind, dew-point temperature, atmospheric pressure at the surface, and incident solar radiation. In order to assist the communication of results to the region’s various stakeholders (ski resorts, policy makers in regional and local administrations) who are usually

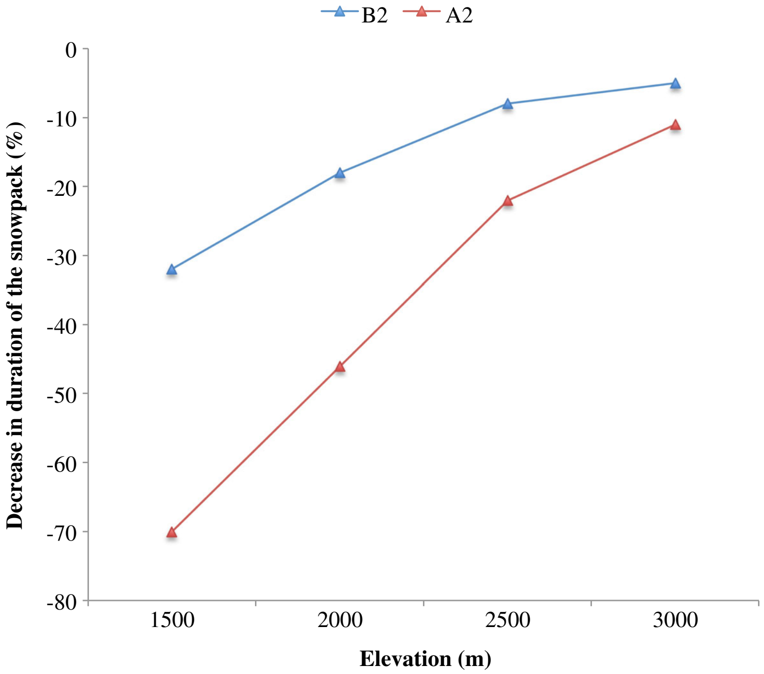

Fig. 3 Simulated changes in the duration of the snowpack according to climate change projected by the HIRH AM model under SRES B2 (*blue*) and A2 (*red*) at different altitudinal planes: 1500, 2000, 2500, and 3000 m

not familiar with climate scenarios and who often have a short-term vision, the nomenclature of these two scenarios was simplified to a +2 and +4 °C increase in the winter mean temperature for the Pyrenean region. Winter is taken to be the ski-season period (from December 1st to April 20th). Hence, the comparison of the projected scenario with a similar past situation (i.e., the 2006–2007 season was similar to the +2 °C scenario) had a stronger impact on local stakeholders' awareness of the situation when communicating results and engaging them in the study.

Figure 4a shows the mean control period (1961–1990) and the future snowpack simulated at average elevation (1900 m) of Ax 3 Domaines (a French ski resort located in the Midi-Pyrénées region with a mean elevation of 1850 m), assuming a +2 °C increase (equivalent to the B2 scenario for the period 2070–2100) and +4 °C increase (equivalent to the A2 scenario for the 2070–2100 period) in winter mean temperature. Figure 4b shows the contribution of snowmaking in enhancing the natural snowpack at 1900 m in the Andorran ski resort of Pal according to the defined parameters for a +2 °C climate change scenario. The figure shows the importance of including this factor in the analysis. Should only natural snow be considered, the resort presented would only have a short period with snow depth over 30 cm, whereas with snowmaking, for most of the winter season, the depth will be above this threshold.

3.2 Vulnerability of the ski resorts

The vulnerability of each ski resort considering both the natural snow and the capacity to produce snow, hereafter referred to as "technical reliability," has been analyzed. Figure 5

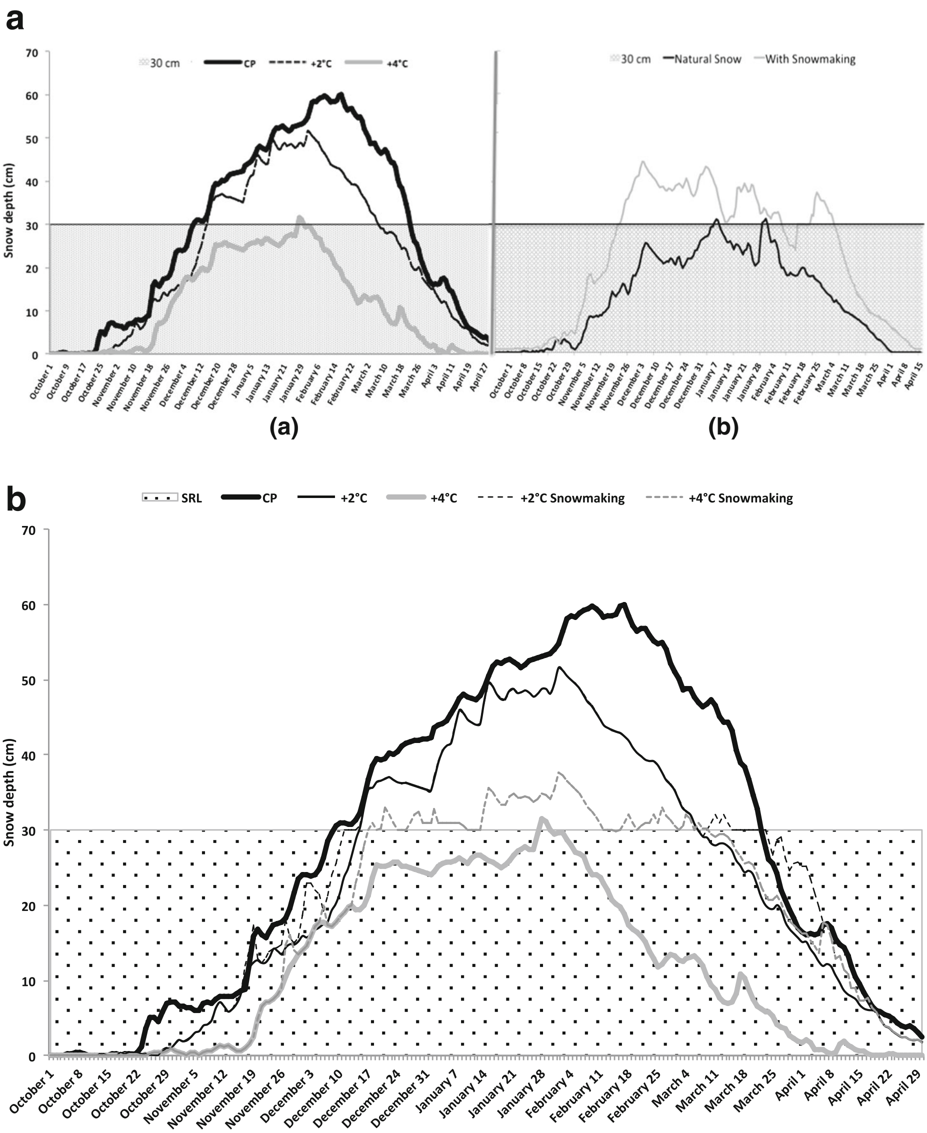

Fig. 4 **a** Mean control period (*CP*), future natural snowpack (+2 and +4 °C) for Ax 3 Domaines (France) ski resort at 1900 m, and the 30-cm threshold assumed as minimum snow depth to consider a resort reliable. **b** Snowpack in Pal (Andorra) assuming a 2 °C increase of the winter average temperature enhanced with snowmaking when the 30-cm threshold is not achieved. **c** Mean control period (*CP*) for Ax 3 Domaines (France) ski resort at 1900 m, future natural snowpack (+2 and +4 °C), enhancement of the future natural snowpack due to the snowmaking, and the 30-cm threshold assumed as minimum snow depth to consider a resort reliable

shows reliable ski resorts with only natural snow as blue dots, those considered reliable thanks to snowmaking systems as yellow dots, and those ski resorts considered as unreliable as red dots, during the two future climate change scenarios, assuming an increase of 2 and 4 °C. The total percentage of ski resorts that are reliable under natural snow conditions and under

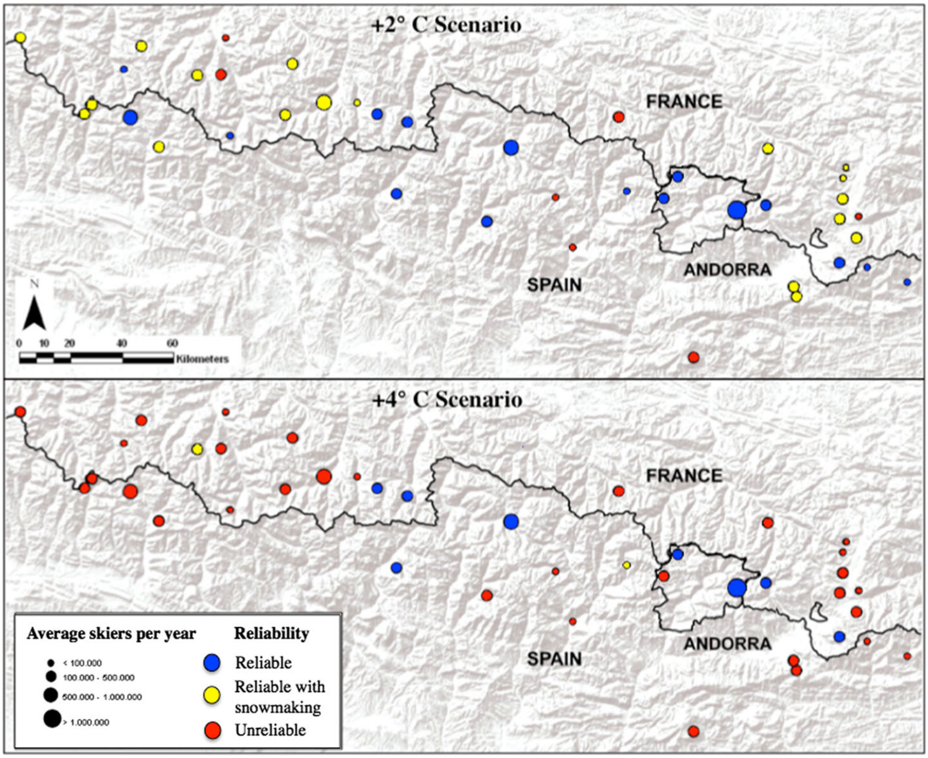

Fig. 5 Reliability of the Pyrenean ski resorts considering only natural snow and natural snow enhanced with snowmaking systems (technical reliability) in two future climate change scenarios: +2 and +4 °C. The size of the *points* represents the present average attendance in number of skiers during the control period

technical conditions (i.e., with snowmaking) in the Pyrenees for the control period (1961–1990), B2 (+2 °C), and A2 (+4 °C) are shown in Fig. 6. At present, 83 % of the ski resorts are considered naturally reliable in an average winter season. However, taking into account snowmaking capacity, 98 % of the ski resorts in the Pyrenees are considered reliable during a current average winter season. In a future scenario, assuming an increase of 2 °C in the winter mean temperature, this share would be reduced to 44 %. In a strong climate change scenario, that is, a scenario assuming an increase of 4 °C, the total share of reliable ski resorts in the Pyrenees would be dramatically reduced to only 7 %. When analyzing the capacity of snowmaking to offset the variability of natural snow, i.e., technical reliability, it has been observed that these systems can largely enhance and extend the season length in a moderate climate change scenario (i.e., 2 °C increase). In this case, the share of technical reliable ski resorts is increased to 85 %. However, in a more intense warming scenario (4 °C), only a residual effect from the snowmaking systems is observed, where no significant increase in the share of reliable ski resorts is projected.

A high variability at short distances has been observed in the level of impacts and therefore in the vulnerability of the different Pyrenean ski resorts. Along this line, it was found that within the same region, two resorts located at a very short distance can have significantly different levels of vulnerability. Factors such as aspect or proximity to the Atlantic Ocean are the main contributors to this high variability.

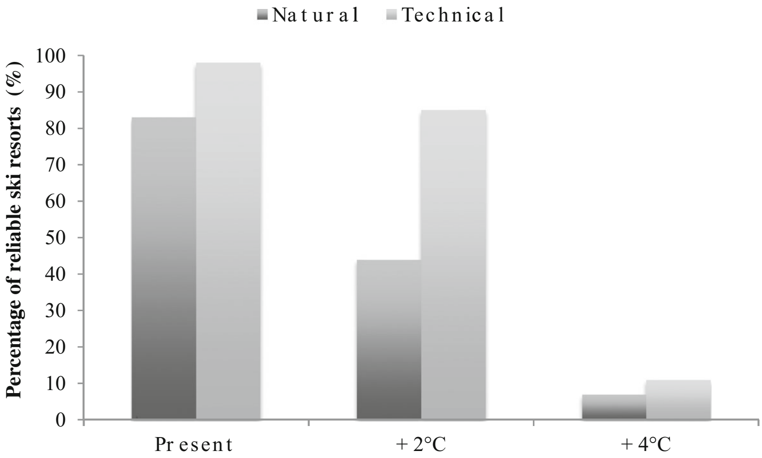

Fig. 6 Share of naturally and technically reliable ski resorts in the Pyrenees in the present and under two climate change scenarios: +2 and +4 °C

4 Discussion

The results achieved in this first approach for the Pyrenean region are in line with the majority of studies published to date that analyze climate change impacts on the ski resorts in different areas around the world. To cite some of them, reductions in the season length in northeast USA have been projected as being around 15 and 41 % (Scott et al. 2008), 15 and 50 % in Ontario (Scott et al. 2008), 5 and 35 % in Quebec (Scott et al. 2007), and 14 and 41 % in Tyrol, Austria (Steiger 2010), taking into account moderate- and high-emissions scenarios, respectively. The projections of the snow model simulations show that the snow depth and the duration of snowpack in the Pyrenean ski resorts may be notably affected by future climate change. Different climate change scenarios lead to significant differences in the severity of the expected changes in the snowpack. Even though there is a high geographic variability in the climate change vulnerability, the reduction of the ski-season length is projected in both a moderate (+2 °C) and a strong climate change scenario (+4 °C).

The snowpack in the eastern areas of the Spanish Pyrenees is clearly the most affected by climate change. Resorts in low-elevation areas, closer to the Mediterranean Sea, and/or with a predominance of south-oriented slopes were identified as being the most vulnerable (season length reduced by around 38 % under the +2 °C scenario). In the particular case of the Pyrenees, those ski resorts closer to the Atlantic Ocean, located at higher elevations, and/or with northerly orientation were identified as being the most resilient (season length reduced by 15 % under the +2 °C scenario) (Fig. 7). Higher altitudes guarantee low temperatures, both for the occurrence of snow precipitation as well as for snowmaking production. The Atlantic influence affects the precipitation pattern, with greater effects on the perturbations associated with polar fronts and enhanced by the mountain ranges that oppose the westerly flows (Vicente-Serrano and Cuadrat 2007). These areas are characterized by more frequent and more equally distributed precipitation throughout the season as compared to a more erratic pattern in the Mediterranean-influenced area, which is usually concentrated in the autumn and spring (Vicente-Serrano and Cuadrat 2007).

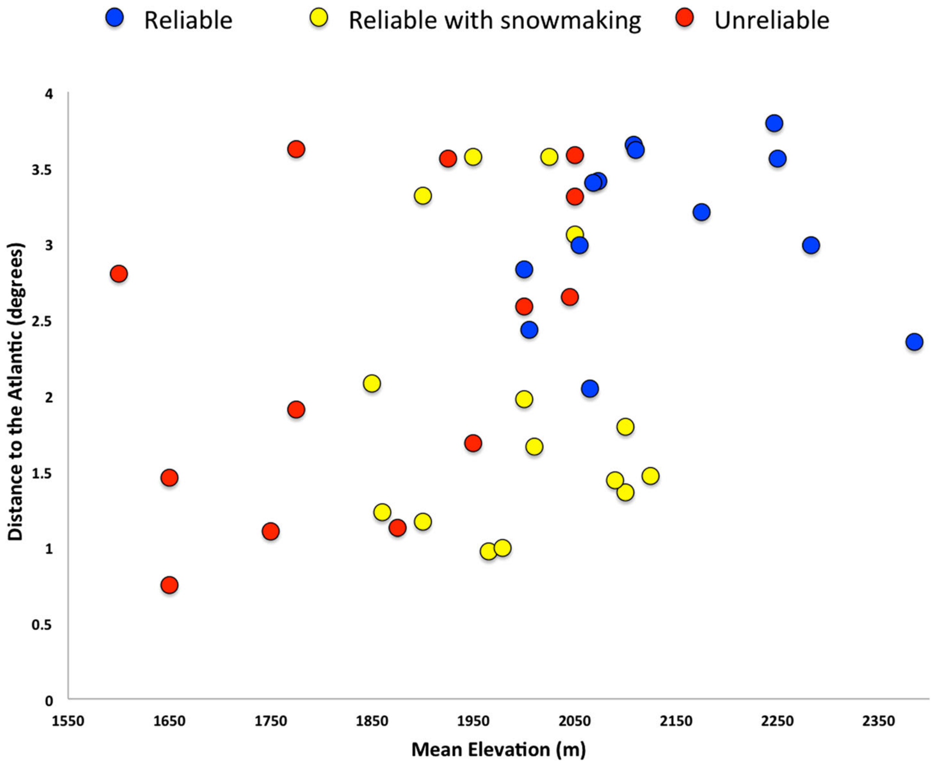

Fig. 7 Reliable ski resorts compared to their elevation and distance to the Atlantic Ocean. *Red dots* show unreliable ski resorts, *blue dots* show those reliable with only natural snow, and *yellow dots* those reliable thanks to snowmaking

The snowmaking analysis showed that under the +2 °C scenario, snowmaking can significantly enhance the ski-season length in many of the Pyrenean ski resorts. However, this measure can only act as a robust adaptation strategy in the region provided climate change is limited to +2 °C snowmaking. In the +4 °C scenario, the capacity of snowmaking significantly reduced due to an increase in the minimum temperature, a determining factor in efficiently producing snow. Therefore, the effect of snowmaking systems is residual in this scenario. The results of this study can be used as the basis for better characterization and understanding of the geographical differences in the vulnerability to impacts due to future climate changes in the region. However, the results illustrated the need for better geographical characterization and higher spatial resolution of the spatial variability of the snowpack in the area.

The spatial distribution of snow in mountain areas is characterized by high variability within very short distances. This variability results from complex interaction between meso-scale meteorology, local topography, and weather factors. Aspect, slope or wind-blown effects (Green and Pickering 2009), or forest density (Lundquist et al. 2013) are crucial factors that affect the spatial distribution of snow. For example, due to the complex topography of mountain areas, slope angle and aspect are also very likely to influence the sensitivity of snowpack to temperature change (Uhlmann et al. 2009). Snowpack dynamics are strongly influenced by aspect (Hinckley et al. 2012), affecting snow accumulation and melting, especially in areas with a marginal snowpack (McNamara et al. 2005). Along this line, it was found that as temperature increases, the effect of aspect on accumulation and melting increases, resulting in greater differences in the maximum snow accumulation and snowpack duration (López-Moreno et al. 2013a, b). Therefore, the inclusion of local topography effects, as well as technical operations on snow (i.e., grooming), when analyzing the future snowpack will be key in achieving a better vulnerability assessment of the Pyrenean winter tourism industry. This information could be complemented in future research with snow cover models with higher spatial resolution, which are better able to capture the regional variability of the snow depth for each ski resort.

4.1 Conclusion

Future climate-induced changes in snowpack of the Pyrenean ski resorts have been projected by means of the GRENBLS model, driven with climatic inputs from the HIRHAM regional climate model. The study shows that snow depth and duration of snowpack in the Pyrenean ski resorts may be strongly affected by future climate change. Based on two future scenarios, the vulnerability of the Pyrenean ski resorts to climate change has been assessed. Different climate change scenarios lead to significant differences in the severity of the expected changes in the snowpack. Even though there is high geographic variability in the vulnerability to climate change, a reduction of the ski-season length is projected both in a moderate (+2 °C) and a strong climate change scenario (+4 °C). Moreover, an analysis of the effects of snowmaking showed that this measure can only act as a robust adaptation strategy in the region provided climate change is limited to +2 °C snowmaking. Finally, the study remarks on the need to improve the inclusion of local topography effects, as well as technical snow operations (i.e., grooming), when analyzing the future snowpack at ski resorts. This issue, complemented with snow cover models with accurate spatial resolution that are better able to capture the regional variability, could significantly improve the climate change vulnerability assessment of ski resorts.

Acknowledgments This work was supported by the research projects Hidrología nival en el Pirineo Central Español: Variabilidad espacial, importancia hidrológica y respuesta a la variabilidad y cambio climático (CGL2011-27536/HID, Hidronieve), financed by the Spanish Commission of Science and Technology and FEDER, the CTTP1/12 "Creació d' un model d' alta resolució espacial per quantificar l'esquiabilitat i l'afluència turística al Pirineu sota diferents escenaris de canvio climàtic," financed by the Governmet of Aragon and ACTP011-AND/2010 and ACTP017-AND/2012 projects financed by the Government of Andorra in the framework of the research grants of Working Community of the Pyrenees. The first author acknowledges also a predoctoral grant from the Andorran Government [BTC2010/2013-0006-AND].

References

Abegg B, Agrawala S, Crick F, De Montfalcon A (2007) Climate change impacts and adaptation in winter tourism. In: Agrawala S (ed) Climate change in the European Alps: adapting winter tourism and natural hazards management. Organization for Economic Cooperation and Development, Paris, pp 25–58

Adam JC, Hamlet AF, Lettenmaier DP (2009) Implications of global climate change for snowmelt hydrology in the 21st century. Hydrol Process 23:962–972

ATUDEM (2013) Dossier de premsa 2012–2013. Associación Tursítica de Estaciones De Esquí y Montaña

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309

Benoît R (1977) On the integral of the surface layer profile-gradient functions. J Appl Meteorol 16:859–860

Bicknell S, McManus P (2006) The canary in the coalmine: Australian ski resorts and their response to climate change. Geogr Res 44:386–400

Botti L, Goncalves O, Peypoch N (2013) Benchmarking Pyrenean ski resorts. J Alp Res 100–104

Breiling M, Charamza P (1999) The impact of global warming on winter tourism and skiing: a regionalized model for Austrian snow conditions. Reg Environ Chang 1(1):4–14

Christensen JH, Carter T, Giorgi F (2002) PRUDENCE employs new methods to assess european climate change. EOS 83, p. 147.

Christensen OB, Christensen JH, Machenhauer B, Botzet M (1998) Very high resolution regional climate simulations over Scandinavia present climate. J Clim 11:3204–3229

Dawson J, Scott D (2007) Climate change vulnerability in the Vermont ski tourism sector. Ann Leis Res 10(34): 550–571

Dawson J, Scott D (2010) Systems analysis of climate change vulnerability for the US northeast ski sector. Tour Plann Dev 7(3):219–235

Dawson J, Scott D, McBoyle G (2009) Analogue analysis of climate change vulnerability in the US northeast ski tourism. Clim Res 39(1):19

De Jong C, Lowler D, Essery R (2009) Mountain hydroclimatology and snow seasonality: perspectives on climate impacts, snow seasonality and hydrological change in mountain environments. Hydrol Process 23: 955–961

DSF (2012) Recueil d'indicateurs et analyses 2012. Domaines Skiables de France

Elsasser H, Bürki R (2002) Climate change as a threat to tourism in the Alps. Clim Res 20:253–257

Endler C, Matzarakis A (2011) Climatic and tourism related changes in the Black Forest: Winter season. International Journal of Biometeorology 55:339-351

Finger D, Heinrich G, Gobiet A, Bauder A (2012) Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century. Water Resour Res 48:W02521

Ford J, Keskitalo ECH, Smith T, Pearce T, Berrang-Ford L, Duerden F, Smit B (2010) Case study and analogue methodologies in climate change vulnerability research. WIREs Climate Change 1(3): 374–392

Fukushima T, Kureha M, Ozaki N, Fujimori Y, Harasawa H (2003) Influences of air temperature change on leisure industries: case study on ski activities. Mitig Strateg Clim Chang 7:173–189

Ganguly AR, Steinhaeuser K, Erickson DJ, Branstetter M, Parish ES, Singh N, Drake JB, Buja L (2009) Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves. PNAS 106(37):15555–15559

Gilaberte M, Pino MR, López F, López-Moreno JI (2015) Impacts of climate change on ski industry. Environ Sci Pol

Gobiet A, Kotlarski S, Stoffel M, Heinrich G, Rajczak J, Beniston M (2014) 21st century climate change in the European Alps. In EGU General Assembly Conference Abstracts 16, 12494

Green K, Pickering CM (2009) The decline of snowpatches in the snowy mountains of Australia: importance of climate warming, variable snow, and wind. Arct Antarct Alp Res 41(2):212–218

Hamlet AF (2011) Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. Hydrol Earth Syst Sci 15:1427–1443

Hantel M, Hirtl-Wielke LM (2007) Sensitivity of Alpine snow cover to European temperature. Int J Climatol 27(10):1265–1275

Hendrikx J, Zammit C, Hreinsson E, Becken S (2013) A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. Climate Change 119:965–978

Hennessy K, Whetton P, Smith I, Bathols J, Hutchinson M, Sharples J (2003) The impact of climate change on snow conditions in mainland Australia. CSIRO Atmospheric Research, Aspendale

Hennessy KJ,Whetton PH,Walsh K, Smith IN, Bathols JM, Hutchinson M, Sharples J (2008) Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snowmaking. Clim. Res. 35:255–270

Hinckley ELS, Ebel BA, Barnes RT, Anderson RS, Williams MW, Anderson SP (2012) Aspect control of water movement on hillslopes near the rain–snow transition of the Colorado Front Range. Hydrological Processes, doi:10.1002/hyp.9549

Intergovernmental Panel on Climate Change IPCC (2007) Climate change 2007: synthesis report. Summary for policy makers. Fourth assessment report. United Nations Intergovernmental Panel on Climate Change, Geneva

Jansson PE, Karlberg L (2004) Coupled heat and mass transfer model for soil-plant-atmosphere systems. Royal Institute of Technology, Department of Civil and Environmental Engineering, Stockholm, 435 pp.

Keller, Goyette (2005) Snowmelt under different temperature increase scenarios in the swiss Alps. Climate and hydrology in mountain areas. Wiley, Chichester, pp 277–289. doi:10.1002/0470858249.ch19

König U, Abegg B (1997) Impacts of climate change on tourism in the Swiss Alps. J Sustain Tour 5(1):46–58

Lamothe and Périard Consultants (1988) Implications of climate change for downhill skiing in Québec. Climate Change Digest 88-03. Ottawa: Environment Canada.

López-Moreno JI, Goyette S, Beniston M, Alvera B (2008) Sensitivity of the snow energy balance to climatic changes: implications for the evolution of snowpack in the Pyrenees in the 21st century. Clim Res 36(3): 203–217

López-Moreno JI, Goyette S, Beniston M (2009) Impact of climate change on snowpack in the Pyrenees: horizontal spatial variability and vertical gradients. J Hydrol 374:384–396

López-Moreno JI, Pomeroy J, Revuelto J, Vicente-Serrano SM (2013a) Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. Hydrol Process 27(18):2637–2650

López-Moreno JI, Revuelto J, Gilaberte M, Morán-Tejeda E, Pons M, Jover E, Esteban P, García C. Pomeroy JW (2013b) The effect of slope aspect on the response of snowpack to climate warming in the Pyrenees. Theor Appl Climatol

Lundquist J, Dickerson-Lange SE, Lutz JA, Cristea N (2013) Low forest density enhances snow retention in regions with warmer winters: a global framework developed from plot-scale observations and modeling

McFarlane NA, Boer GJ, Blanchet JP, Lazare M (1992) The Canadian climate centre second generation general circulation model and its equilibrium climate. J Clim 5:1013–1044

McNamara JP, Chandler D, Seyfried M, Achet S (2005) Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt driven catchment. Hydrol Processes 19:4023–4038

Minder JR (2010) The sensitivity of mountain snowpack accumulation to climate warming. J Clim 23:2634–2645

Moen J, Fredman P (2007) Effects of climate change on alpine skiing in Sweden. J Sustainable Tourism 15:418–437

Mote PW (2003) Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophys Res Lett 30(12):L1601

Nogués-Bravo D, Araújo MB, Errea MP, Martínez-Rica JP (2007) Exposure of global mountain systems to climate warming during the 21st century. Glob Environ Chang 17:420–428

Nolin AW, Daly C (2006) Mapping “at risk” snow in the Pacific Northwest. J Hydrometeorol 7:1164–1171

Pomeroy JW, Gray DM, Hedstrom NR, Quinton WL, Granger RJ, Carey SK (2007) The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence. Hydrol Process 21:2650–2667

Pons M, Johnson AP, Rosas-Casals M, Jover E (2014) A georeferenced agent-based model to analyze the climate change impacts on ski tourism at a regional scale. J Geogr Inf Sci 28(12):2474–2494

Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A (2008) Declining summer flows of rocky mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests. J Hydrol 349: 397–410

Saurí D, Llurdés JC (2010) El Turisme. In: Llebot JE (ed) Segon Informe sobre el Canvi Climàtic a Catalunya. Generalitat de Catalunya, CADS, Barcelona, pp 836–871

Scott D (2011) Why sustainable tourism must address climate change. J Sustain Tour 19(1):2011

Scott D, McBoyle G (2007) Climate change adaptation in the ski industry. Mitig Adapt Strateg Glob Chang 12(8):1411–1431

Scott D, McBoyle G, Mills B (2003) Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. Clim Res 23:171–181

Scott D, McBoyle G, Mills B, Minogue A (2006) Climate change and sustainability of ski-based tourism in eastern North America: a reassessment. J Sustain Tour 14(4):376–398

Scott D, McBoyle G, Minogue A (2007) Climate change and Quebec’s ski industry. Glob Environ Chang 17: 181–190

Scott D, Dawson J, Jones B (2008) Climate change vulnerability of the US northeast winter recreation tourism sector. Mitig Adapt Strateg Glob Chang 13:577–596

Scott D, Gössling S, Hall CM (2012) Climate change and tourism: impacts, adaptation and mitigation. Routledge, London, p 423

Ski Andorra www.skiandorra.ad. Last access November 21st 2013

Steiger R (2010) The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. Clim Res 43(3):251–262

Steiger R (2011) The impact of snow scarcity on ski tourism: an analysis of the record warm season 2006/2007 in Tyrol (Austria). Tourism Review 66(3):4–13

Steiger R (2012) Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. J Sustain Tour 20(6):867–882

Steiger R, Abegg B (2013) The sensitivity of Austrian ski areas to climate change. Tour Plann Dev 10(4):480–493

Steiger R, Mayer M (2008) Snowmaking and climate change. Future options for snow production in Tyrolean ski resorts. Mt Res Dev 28:292–298

Tague C, Dugger AL (2010) Ecohydrology and climate change in the mountains of the Western USA—a review of research and opportunities. Geogr Compass 4(11):1648–1663

Trujillo E, Molotch NP, Goulden ML, Kelly AE, Bales RC (2012) Elevation-dependent influence of snow accumulation on forest greening. Nat Geosci 5:705–709

Uhlmann B, Goyette S, Beniston M (2009) Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature, precipitation and humidity under condition of climate change. Int J Climatol 29:1048–1055

Vanat L (2014) 2014 International report on snow & mountain tourism

Verseghy DL (1991) CLASS—a Canadian land surface scheme for GCMs. I. Soil model. Int J Climatol 11:111–133

Vicente-Serrano SM, Cuadrat JM (2007) Trends in drought intensity and variability in the middle Ebro valley (NE Spain) during second half of the twentieth century. Theor Appl Climatol 88:247–258

Witmer U (1986) Erfassung, Bearbeitung und Kartierung von Schnee daten in der Schweiz. Geographica Bernensia G25