Climate Change Impacts on Winter Tourism in the Pyrenees and Adaptation Strategies

by

Marc Pons

A thesis
presented to the Universitat Politècnica de Catalunya
in fulfillment of the
thesis requirement for the PhD
in
Sustainability

Barcelona, 2014

If you are faced with a mountain, you have several options. You can climb it and cross to the other side. You can go around it. You can dig under it. You can fly over it. You can blow it up. You can ignore it and pretend it's not there. You can turn around and go back the way you came. Or you can stay on the mountain and make it your home.

Vera Nazarian[1]

---

[1] In *The perpetual calendar of inspiration.Old Wisdom for a New World*. Norilana Books, Vermont 2012

CONTENTS

ABSTRACT

Climate change has become no longer a conjecture but an objective reality. The increase of the global average temperature, the seas level rise or the increase in the frequency and magnitude of extreme weather events are some examples observed during the past century that have turned the global warming into a sharply contrasted evidence. In this context of climate change, mountain regions have been defined as especially vulnerable areas. The rapid retreat of glaciers and permafrost surfaces, the decrease of snow precipitations, the increase of natural risks such as landslides or the alteration in the amount and distribution of some species prove the high sensitivity of mountain ecosystems. Moreover, in many mountain economies, reliable snowpack plays a key role as an important resource for the winter tourism industry, one of the main income source and driving force of local development in such regions. For this reason, research on the effects of climate change on the snowpack depth and duration is particularly necessary in order to assess the potential socioeconomic impacts in mountain regions. On the other hand, in recent years and sometimes thanks to public subsidies and interventions, ski resorts are investing huge amounts of money in snowmaking infrastructures. By means of this policy, it is expected to offset the effect of climate variability and guarantee the snowpack necessary to assure reliable ski seasons every year. However, not all ski resorts will be able to offset or attenuate their vulnerability by means of snowmaking, either due to economic constraints or due to the severe environmental impacts related to this adaptation strategy. Moreover, a future rising of temperatures could constrain the efficiency and viability of these systems. If we focus on Andorra and the Pyrenees, there is a research gap due to a clearly lack of academic studies in this field. For this reason, it is not accurately known how climate change will affect the ski industry and which are the most suitable adaptation strategies for this specific region.

The main goal of this research is to analyze how climate change could affect the snow cover and the snowpack in the Pyrenean ski resorts and to assess the resulting vulnerability of the ski industry of this region. In order to estimate future season length, changes in the snowpack depth and duration have been projected for each ski resort. Most of the available literature is focused on the demand-side impacts on ski industry. Even though several studies have pointed out the intrinsic importance of weather and climate for tourist decision-making and that behavioral adaptation of tourists due to spatial, temporal and activity substitution could exert a strong influence, no study has included this issue on the final output of the climate change impact assessments. Thus, the adaptive behavior of skiers to climate change has been included in the analysis in order to analyze the potential redistribution of visitors among the ski resorts due to heterogeneous climate change vulnerability. Based on the results, this study analyzes the suitability and sustainability of the adaptation techniques and strategies to offset the climate variability, first in a case study of Andorra in order to develop a preliminary model and finally extending the analysis to the whole Pyrenees in order to assess the potential concurrence among ski resorts with differentiated climate vulnerability and tourism attractiveness and the resulting redistribution of skiers based on their behavioral adaptation to climate effects.

Four different scenarios are considered. Two scenarios assume an increase of winter mean temperature of +2°C and +4°C respectively, taking into account only natural snow conditions. Two additional scenarios add the effect of snowmaking to enhance the natural snow depth and extend the skiing season in the +2°C and +4°C base scenarios. Results show differing vulnerability levels, allowing the classification of ski resorts into three distinct groups: (1) highly vulnerable ski resorts with a strong reduction in visitors attendance for all climate change scenarios, characterized by unfavorable tourism attractiveness and geographical conditions, making it difficult to ensure snow availability in the future; (2) low vulnerability ski resorts, with moderate reduction in season length during a high climate change scenario but no reduction (or even an increase) in a low one, characterized by ski resorts with a medium attractiveness and capacity to ensure enough snow conditions and capture skiers from other ski resorts; and (3) resilient ski resorts, with good conditions to ensure future snow-reliable seasons and outstanding attractiveness, allowing them to offer longer ski seasons than their competitors and potentially attracting skiers from other closed or marginal resorts. Ski resorts included in this last group increase their skier attendance in all climate change scenarios. Moreover this study intends to overcome the gap in literature about the influences of the demand-side when analyzing climate change impacts on winter tourism. In this way, although similar studies, only including supply-side changes, foretell a significant reduction of the ski market in the near future, this thesis projects a redefinition of the winter ski market due to a redistribution of skiers, from vulnerable ski resorts to more resilient ones.

ACKNOWLEDGEMENTS

First I would like to sincerely thank Dr. J.I. López-Moreno for all the shared data and knowledge that have been the base, pillar foundation and starting point for this research. I feel really fortunate for all the support, guidance, good talks and laughs shared through this project, that I am sure will be the first of many more.

Thanks also must be given to Dra. Barbara Sureda, for all her support during the first stages of this research and to all my colleagues of the SUMMlab and OBSA.

I would also like to thank Dr. Peter A. Johnson for his support during the fruitful research stays with him and his significant contribution to the improvement of the modeling process and analysis.

A special thank must given to Dr. Daniel Scott and Dr. Robert Steiger for the reviewing and helpful feedback that has improved the quality of this research.

I would also like to acknowledge the financial support provided by the Andorran Government both for a predoctoral grant (BTC2010/2013-0006-AND) and CTP projects funding (CTTP1/10 and CTTP1/12) and all the partners of the NIVOPYR project (IPE-CSIC, CENMA, IGC, Centre de Lauegi d'Aran) for their contribution and support during these years.

1. Climate change, snow tourism and sustainability

> *One of the big questions in the climate change debate: Are humans any smarter than frogs in a pot? If you put a frog in a pot and slowly turn up the heat, it won't jump out. Instead, it will enjoy the nice warm bath until it is cooked to death. We humans seem to be doing pretty much the same thing.*
>
> **Jeff Goodell**
> **Fracking, Nukes and More**

1.1 Human-Environment interactions and Sustainability

One main argument for studying socio-ecological systems is to advance the understanding of the dynamic interrelationship between various human and environmental factors, including impacts and responses to environmental changes. The surrounding environment, and how it changes over time, influences and constrains the development of any human activity. At the same time, human activities never are totally neutral to the environment, constantly changing its resources and its current state. Global environment has always evolved and changed throughout earth and human history due both to natural processes and humans interactions. However, in the last century the level and rate of change induced by human factors has grown exponentially, leading to an increase of the stress to the planet's resources and ecosystems, exceeding its carrying capacity and jeopardizing the ability to sustain future generations (Meadows et al., 2004). In 1983, the UN General Assembly set up the World Commission on the Environment and Development (WCED) with the Norwegian Labour Party leader, Gro Harlem Brundtland as the chairperson. *Our Common Future*, better-known as the Brundtland Report, was the result of this commission with the aim of raising the awareness about the dangerous trend of increasing human impact on the environment and claiming for a "sustainable development which meets the needs of present without compromising the ability of future generations to meet their own needs" (WCED 1987). The report intended to set the principles of the Sustainability as the achievement of a balance between economic, environmental and social concerns by means of a holistic planning and strategy-making, preserving essential ecological processes, biodiversity, human heritage and based on a development able to be sustained over the long term for future generations. Based on intergenerational-intragenerational equity, the report supported the unlimited economic growth taking into account that indeed there are limits to physical growth (Dresner 2002). Since then, the concept of Sustainability has spread and evolved following different lines of thought, from more anthropocentric points of views, such as the Brundtland report, to more ecocentric ones, considering the carrying capacity of ecosystems as the main constrain to any kind of physical or economical growth (Daly and Cobb 1990).

1.2 Climate change

The most paradigmatic example of how human activity can lead to a global environmental change is probably the present climate change. In the last decades the plausibility of a human-induced climate change has moved from a contentious conjecture to an objective reality. The sea level rise, the melting of the glacier caps, the increase of the global average temperature or the increase in the frequency and magnitude of extreme weather events are some examples noticed during the past century that have turned the global warming, even though still controversial, into a sharply contrasted evidence (IPCC, 2013).

Throughout history, the planet Earth has always undergone periodic changes on its climate due to physical processes such as changes on the earths' orbit, Milankovitch cycles (Milankovitch, 1998), the solar cycles, the movement of tectonic plates or driven by volcano eruptions (Weart, 2003). However, the rate and abruptness of present climate change has no precedent in the recorded history of planet earth (Weart, 2003). In recent years, scientific community agrees that this rapid change is due mainly to the enhancement of the natural greenhouse effect due to a human-induced increase in the atmospheric concentration of green house gases (GHGs), such as carbon dioxide (CO_2) or methane (CH_4). The presence of these gases in the atmosphere exert a greenhouse effect, being transparent to incoming solar radiation but absorbing and reflecting again the infrared radiation from the earth surface and resulting in the rising of the average surface temperature (figure 1.1).

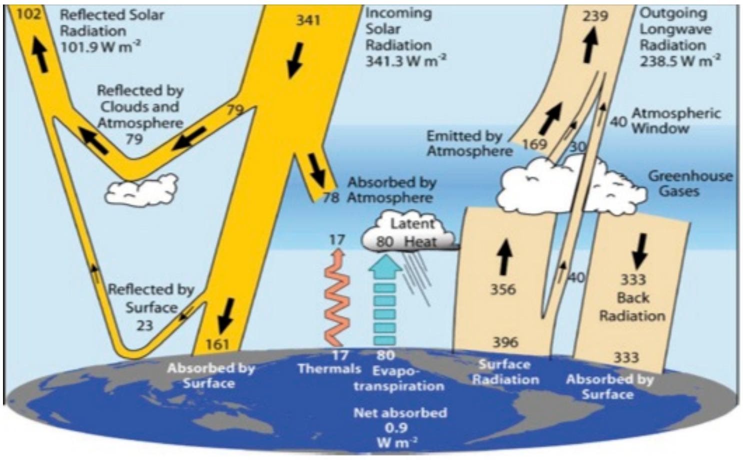


Figure 1.1. Climate system energy balance showing the most important mechanisms involved in the energy exchange between the lower atmosphere and the Earth's surface, for example, the effect of greenhouse gas emissions and other forcing mechanisms on climate (IPCC, 2007).

The shift in the atmospheric concentration of GHGs is highly correlated with the changes on the past average surface temperature of the planet earth and has been identified as one of the main forcing mechanisms for the earth climate. Figure 1.2 shows the correlation between the changes on the average surface temperature over the last 800.000 years obtained from Antarctic ice cores and the changes on CO_2 concentration in the atmosphere.

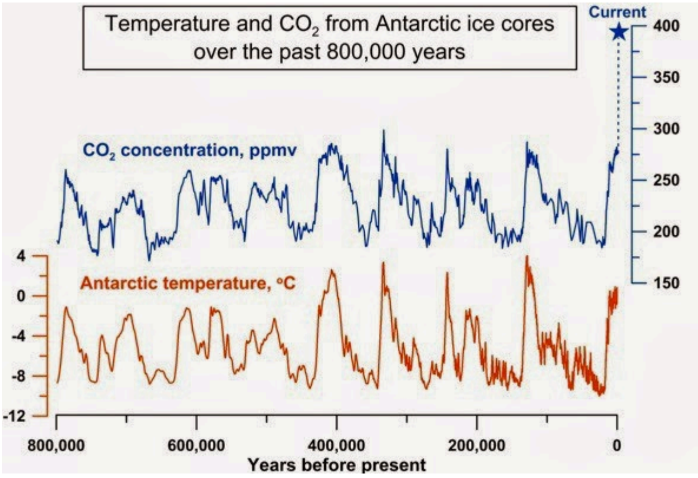


Figure 1.2. The 800.000-year record of the atmospheric CO_2 from the EPICA C and Vostok ice cores, and reconstruction of local Antarctic temperature based on deuterium/hydrogen ratios in ice and the CO_2 atmospheric concentration (Lüthi et al., 2008).

In the past century, the rapid growth of economic activity, especially in the last few decades, and mainly the intensive use of fossil fuels led to an abrupt and dramatic increase of the atmospheric green house gases (figure 1.3). The combustion of fossil fuels, such as oil and coal are the principal sources of emission of these kinds of gases and have been identified as the most significant driver of the current climate change (IPCC, 2013). About half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 have occurred in the last 40 years. In 1970, cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring since 1750 were 420 $GtCO_2$. In 2010, that cumulative total had tripled to 1300 $GtCO_2$. Emissions from forestry and other land use, also affecting atmospheric concentrations of GHGs, increased from 490 $GtCO_2$ in 1970 to 680 $GtCO_2$ in 2010 (IPCC, 2013).

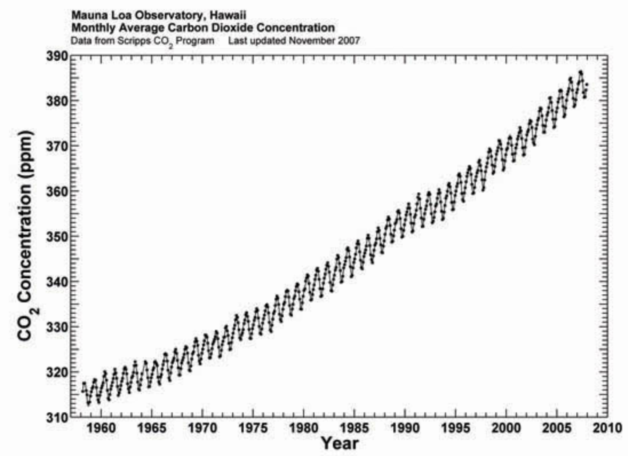


Figure 1.3. Level of CO_2 in the atmosphere, 1958-2007. Source: Scripps Institution of Oceanography.

The Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate change, is devoted to gather and compile all the published research and release periodic updates of the current knowledge on climate change. Besides the understanding of the past and recent changes, scientific community is continuously working on models able to project the future changes on climate. In this line, IPCC proposed different scenarios of future climate change based on different assumption for greenhouse gas and aerosol emissions, land-use, economic and technological development and other diving forces. Figure 1.4 shows projections of future global average surface temperature for various IPCC scenarios (Representative Concentration Pathways, RCP). Solid colored lines represent "most likely" trends; shaded regions represent "probable ranges". The gray bars on the right represent year 2100 temperatures for all four scenarios; the colored stripe represents the "best estimate", while the shaded gray region represents "likely ranges". The different scenarios and models predict temperature changes between one and more than four degrees Celsius by the end of this century.

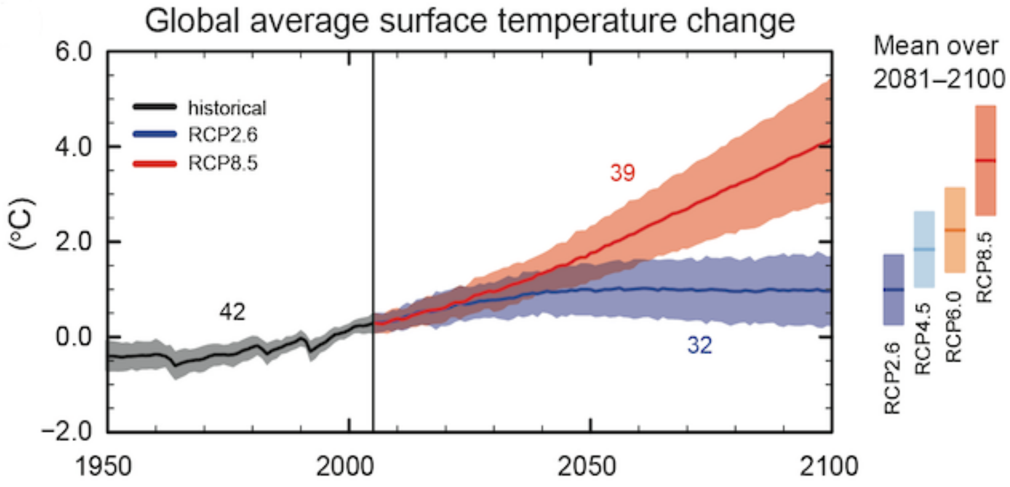


Figure 1.4. Projections of future global average surface temperature for various IPCC scenarios (IPCC, 2013).

Temperature increases are expected to be greater on land than over oceans and at high latitudes than in the tropics and mid-latitudes. Moreover, heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length. Higher average global temperatures will cause a higher overall rate of evaporation, resulting in higher overall rates of precipitation. The global water cycle will be enhanced, leading to more water vapor into the atmosphere falling back again as rain and snow. Changes in precipitation are expected to be more heterogeneous and uncertain that changes in temperature having a high temporal and spatial variability. Some locations could suffer and increase of rain and snow precipitations, while other could experience significant reductions. Moreover, models predict an increase on the frequency of extreme precipitation as well as a tendency for drying of the mid-continental areas during summer, indicating a greater risk of floods and droughts in those regions (IPCC, 2012).

Proxy and instrumental data indicate that the rate of global sea level rise has accelerated during the last two centuries, making the transition form relatively low rates of change during the late Holocene (order tenths of mm yr-1) to modern rates (order mm yr-1). It is very likely that the mean rate was 1.7 mm yr-1 between 1901 and 2010 for a total sea level rise of 0.19 m. Between 1993 and 2010, the rate was very likely higher at 3.2 mm yr-1; similar high rates occurred between 1930 and 1950. The global sea has accelerated since early 1900s, with estimates ranging from 0 to 0.013 [-0.002 to 0.019] mm yr-2. Regarding sea level rise projections, for an unmitigated future rise in emissions (RCP 8.5 scenario), IPCC now expects between a half meter and a meter of sea-level rise by the end of this century. The best estimate here is 74 cm. On the low end, the range for the RCP2.6 scenario is 28-61 cm rise by 2100, with a best estimate of 44 cm. Now that is very remarkable, given that this is a scenario with drastic emissions reductions starting in a few years from now, with the world reaching zero emissions by 2070 and after that succeeding in active carbon dioxide removal from the atmosphere. Even so, the expected sea-level rise will be almost three times as large as that experienced over the 20th Century (17 cm). This reflects the large inertia in the sea-level response – it is very difficult to make sea-level rise slow down again once it has been initiated. This inertia is also the reason for the relatively small difference in sea-level rise by 2100 between the highest and lowest emissions scenario (the ranges even overlap) – the major difference will only be seen in the 22nd century (IPCC, 2013).

Climate change will also affect biological systems and the global carbon cycle. Temperature changes affect the ecologic niches of many types of plants and animals. The geographical distributions or the lengths of growing seasons will be significantly affected by a climate change. All these changes in biodiversity amount and distribution can lead to significant impact both in wildlife and in agriculture species (IPCC, 2014).

In spite the uncertainty in the level and the time horizon of the projected changes, especially at regional scale, the main trends of the potential shifts on the climatic system, and therefore the potential impacts, are better known. In this context, mountain regions have been identified as especially vulnerable areas to climate change impacts. The rapid retreat of glaciers, important changes in snowfall amount and frequency and shifts in biodiversity amount and distribution are some examples that demonstrate the sensitivity of mountain ecosystems (Messerli and Ives, 1990; Beniston 2003; IPCC, 2014). Moreover, in many mountain economies, reliable snowpack plays a key role as an important resource for the winter tourism industry, one of the main income source and driving force of local development in such regions (Beniston 2003; UNWTO, 2003; 2008; Saurí and Llurdés, 2010).

1.3 Climate change in mountain regions

Mountain regions are unique areas for the detection and the assessment of climate change impacts. In recent decades, a significant increase in temperature has been detected in the majority of the mountain regions around the world (Pepin and Seidel, 2005; Díaz and Eeischeid, 2007; Pepin and Lundquist, 2008; Ohmura, 2012). The temperature increase in these regions has been detected to be higher than global average change (Beniston, 2004; Esteban et al., 2012). Even though the uncertainties and the large regional variability, climate models project that temperature will continue to increase in coming decades (Ganguly et al., 2009). Mountain areas are expected to be particularly affected by high rates of warming and climate scenarios project a greater temperature rise in mountain than at lower altitudes (Giorgi et al., 1994; Bradley et al., 2006; Nogues-Bravo et al., 2008; Barrera-Escoda and Cunillera, 2011; ESCAT, 2012; SCAMPEI, 2012) with consequent impacts on the accumulation and duration of mountain snowpacks (Adam et al., 2009; García-Ruiz et al., 2011). This warming has been generally accompanied by a shift toward earlier snowmelt and declining snow accumulation (Mote, 2003; Barnett et al., 2005). Snow cover and snowpack respond also very rapidly to changes in the patterns of temperatures and precipitations. Many academic studies have identified and analyzed the changes in the seasonality and the amount of snow due to climate change (Brown and Robinson, 2011; Brown and Mote, 2009; Déry and Brown, 2007, López-Moreno and Serrano-Vicente, 2007). This change in snowpack dynamics is a consequence of the great sensitivity of snow to temperature increase, which causes a decreasing proportion of snowfall relative to rainfall, and an increase in available energy for snow melting. Increasing temperature could turn snow precipitation into more often rain precipitation in many temperate mountain climates (Rood et al, 2008). These changes in the snow cover and snowpack duration could strongly affect the water resources and the mountain biodiversity (IPCC, 2013). Ozenda and Borel (2001) have demonstrated that vegetation of snowy areas is more vulnerable to climate change because is more exposed to the drainage in summer. In many regions, especially those with a higher continental and Mediterranean influence, the increase in the temperatures and the frequency and severity of canicula periods, could enhance and move to early spring the melting of the snow cover (López-Moreno et al., 2008b).

Moreover, the abrupt topography and the marked altitudinal gradient result in significant climate variations at short distances, affecting both physically and biologically the ecosystems of these regions. For this reason, mountains host a great biodiversity with strong transitions in ecotons, such as abrupt changes from vegetated lands to snow or ice lands (Whiteman, 2000). Furthermore, mountain ecosystems are often peopled with endemic species, isolated in small ecological niches in high altitude lands. Such systems, highly sensitive, will be, and they already are, highly affected by changes in the climatic patterns. For example, the detected rise of temperatures is moving the ecological niche of several mountain species to higher elevations, reducing the available land and consequently reducing its population or even leading to the their extinction (Peters and Darling, 1985; Hansen-Bristow et al., 1988; Cumming and Burton, 1996). Regarding to hydrology, the increasing temperatures will affect the temporality and the dynamics of the water cycle. Even though, the trend and the direction of precipitations changes due to climate changes are still uncertain and will vary significantly from one region to another. In this way, it is mainly expected that climate change would lead to an increase in the amount of rain precipitation and a decrease in the snow precipitation in mountain areas (Rood et al., 2008). However, there are also some studies showing that some high elevation locations could experience an increase of the snowfalls (López-Moreno, 2009). Shifts in the amount and temporality of precipitations will affect the runoff, the soil moisture, the water reservoirs or the level and frequency of draughts and floods (López-Moreno et al., 2008b). These changes will lead to impacts not only on the mountain regions but also in all those lowlands areas influenced by the basins depending on the mountain resources. Because mountain areas are the source of approximately 50% of the world rivers, climate change could have a strong economic and social impact in densely populated areas far away from mountains affecting the water availability for domestic uses, hydropower energy or industrial uses (Beniston 2003).

Another apparent proof of climate change in alpine spaces is the evolution of glaciers in the last century. Glaciers are a valuable indicator due to the high sensitivity to changes in the temperature and precipitation regimes and represent one of the most visible evidences of current climate change (Haeberli et al., 2005; Zemp et al., 2006). The volume of ice in the glaciers is based on the balance between the snow and the ice accumulation (input) and the melting, sublimation and separation of ice blocks (outputs). All these factors are regulated by temperature, humidity, wind and other topographic factors such as the slope and the albedo of the ice (Fitzbarris et al., 1996). With the increase in temperatures due to climate change this balance has been strongly affected. For example, the glaciers in the European Alps reached their recent maximum extent around 1850 (Holszhauser and Zumbühl, 2003; Haeberli et al., 2005). The overall are loss since then is estimated to be about 35% until the 1970s, when the glaciers covered a total area of 2.909 km^2, and almost 50% by 2000 (Zemp et al., 2006). Total ice volumes in 1850, 1970s and 200 are estimated to be about 200 km^2, 100 km^2 and 75 km^2, respectively (Zemp et al., 2006). After 1985, an acceleration in glacial retreat has been observed, culminating in an annual ice loss of 5-10% of the remaining ice volume in the extraordinarily warm year of 2003 (Zemp et al., 2005). Figure 1.5 shows the changes on the surface of the Austrian Hornkees glacier from 1905 to 2003 and Pasterze glacier from 1930 to 2000.

Figure 1.5. Changes in the surface of the Hornkees glacier (a) from 1905 to 2003 and in the Pasterze Glacier (b) from 1930 to 2000, in Austria. Source: Gesellschaft für Ökologische Forschung.

In the particular case of the Pyrenees, since 1945, it has been observed a rise in temperature of +1,3°C (Lavaud, 2008; Météo-France/ARPE, 2008). Moreover, since 1951 the days with more than 25°C have been significantly increased as well as the number and duration of droughts. Even though there is a high uncertainty and variability on the temporality and magnitude of projected changes, all model projections are congruent in the increase of temperatures in the Pyrenees both for summer and winter seasons. Figure 1.6 shows the uncertainty and the potential range of future changes in maximum winter temperature under different emission scenarios and using different climate models. The projected temperature increases range from 1.1°C-1.9°C in the short-term to 2.1°C-4°C in the long-term.

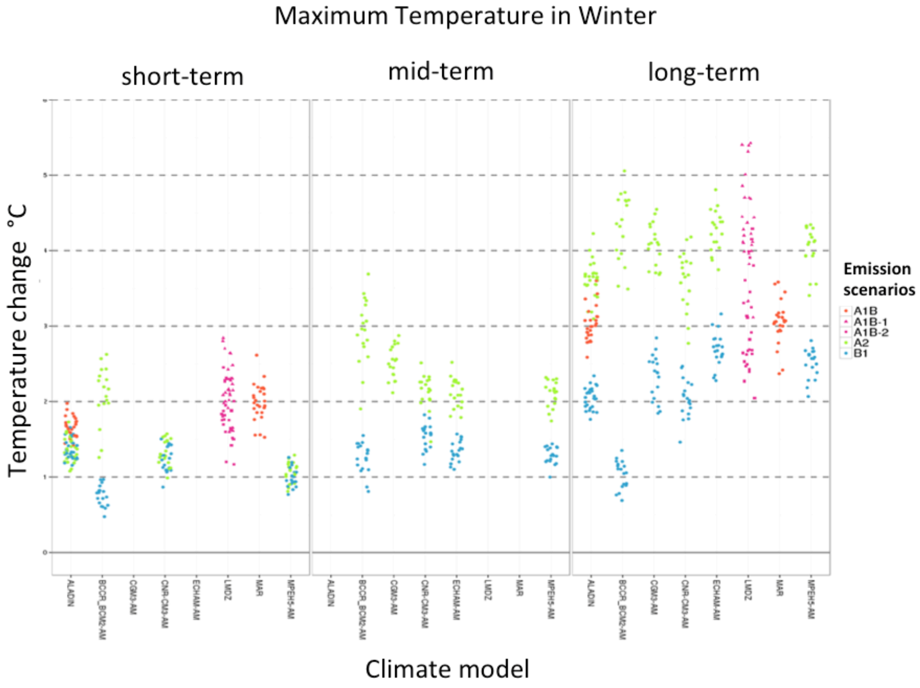


Figure 1.6. Short (2020-2050), mid (2040-2070) and long-term (2070-2100) projected changes on the maximum temperature in winter (DJF) in different locations (colored dots) in the Pyrenees for different climate models and different emissions scenarios. Esteban from Météo-France (SCAMPEI, 2012) and AEMET (Brunet et al., 2009) in Pons et al., 2014.

On the other hand, the projected changes in precipitation patterns are subjected to a higher uncertainty and spatial variability depending on the climate model used for the projections. This variability leads to very different and opposite effects on short distances, having subregions expecting an increase of the precipitations and others expecting significant or dramatic decreases. Although this variability in the expected precipitation patterns, the increased temperatures are expected to shift frequent snowfalls to more frequent rain precipitation, specially at low elevation areas. In this line, changes in temperature could be more influent than precipitation changes in the future snowpack and snow cover, specially reducing them in low elevation areas. López-Moreno et al., (2013) found that a change of +1°C was reported to cause a 20% reduction in accumulated snow water equivalent, and a noticeable shortening of snowpack duration. Etchevers and Martin (2002) found that an increase in the average temperature of +2°C could lead to a 25-50% decrease of the current snow cover of low elevations areas of the Pyrenees. In high elevation areas the expected change would be around -20% of the current snow cover.

Some other identified effects of climate change on the Pyrenees are the 85% of reduction in glacier surfaces since 1950, the increase in altitude of plant species in 3 meter per year since 1971 or the 15 days earlier harvest in the eastern Pyrenees (OPCC).

Finally, the close relationship and interdependence between ecosystems and social systems in mountain areas turn these regions into highly dependent of the available natural resources and highly sensitive to their changes. Figure 1.7 summarizes the main climate change impacts in mountain regions and the close relationship between physical and biological changes and the resulting economical and social impacts. As previously indicated, changes in the water cycle could lead to impacts on the water availability for domestic, industrial or energy uses. Changes in biodiversity could lead to changes in the land productivity and agriculture habits (Beniston, 2003). However one of the main economic activities that would be affected by a global warming is the winter tourism, one of the main sources of income and development in many mountain regions.

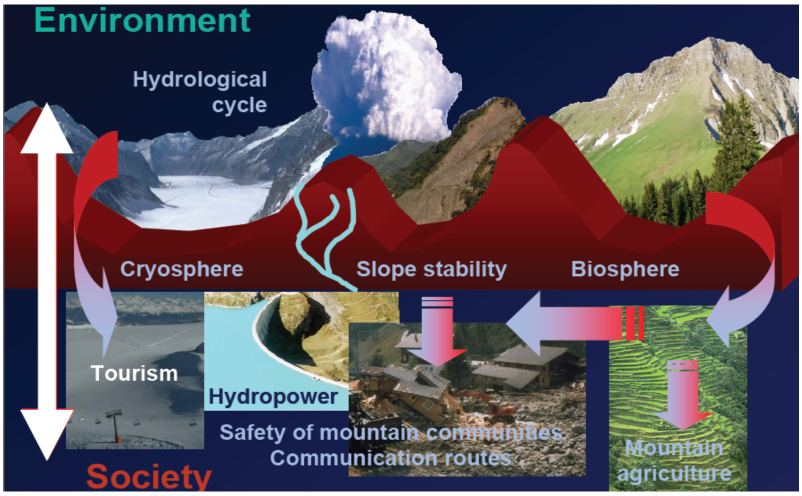


Figure 1.7. Climate change impacts on mountain regions. Source: Beniston, 2003.

1.4 Climate change and tourism

Tourism is considered one of the most climate-sensitive economic activities. Most tourism destinations are dependent on climate and weather, such as sun or winter destinations (UNWTO-UNEP-WMO, 2008). The relationship between tourism and climate change is complex and occurs at multiple scales representing both a resource and a constraint for this industry (Scott et al., 2012) (Figure 1.8). As De Freitas (2003) defined it there are three facets of climate acting as a resource for tourism:

- The thermal component: Relates to the thermal comfort (air temperature, wind, solar radiation, humidity, metabolic rate, clothing and activity).
- The physical component: Represents features such as wind and precipitation (rain/snow) that may limit the possibility for tourist activities or act as a physical annoyance.
- The aesthetic component: Refers to climate features that may influence tourists' appreciation of a view or landscape.

The integrated effect of these facets has a significant influence both in the capacity to offer activities and the tourist decision-making process to travel and be engaged in any activity. Weather and climate are a key factor considered during travel planning, influencing not only tourist activity choices and expenditure but also the timing of travel. Furthermore the climate has a direct effect on the availability and distribution of environmental resources used as tourism resources such as biodiversity, snow, glaciers or water bodies. On the other hand, tourism industry is at the same time one of the main contributors to climate change accounting around a 5% of the global Green House Gases (GHGs) emissions. These emissions are mainly due to transport and energy use for tourism infrastructures such as accommodation and those related to tourist activities (Scott et al., 2012).

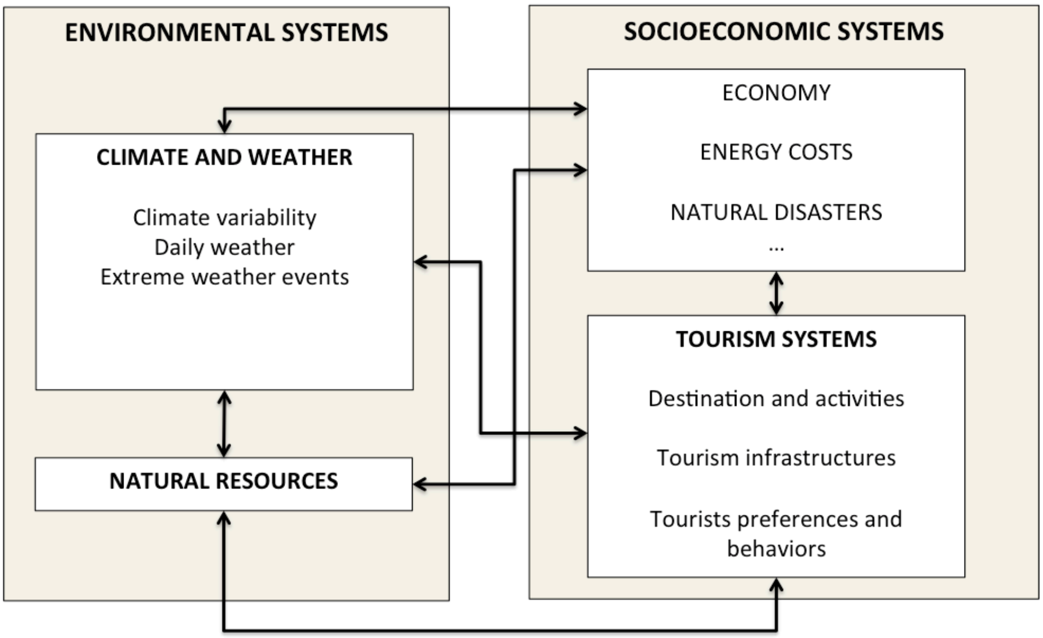


Figure 1.8. Interactions between socioeconomic/tourism systems and environmental/climate systems (Adapted from Scott et al., 2012).

This strong relationship and interdependence between tourism and climate, previously discussed in the Djerba (UNWTO-UNEP, 2003) and Davos Declarations (UNWTO-UNEP-WMO, 2008) led the United Nations World Tourism Organization (UNWTO), the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to identify climate change as the "greatest challenge to the sustainability of the global tourism industry in the 21st century" (UNWTO-UNEP-WMO, 2008). Since this milestone, academic literature and research about how future climate change will affect future distribution, patterns and tourism dynamics has grown rapidly covering many different kinds of tourism and regions across the world (Scott et al., 2012). In this context, winter tourism, highly dependent on a specially climate-threatened resource as is the snow, has been identified as one of the most climate vulnerable type of tourism (UNWTO-UNEP-WMO, 2008).

1.5 Climate change and winter tourism

Even though climate and weather are only one of the factors affecting winter tourism, the close relationship between them turns the comprehension of the climate change impacts on winter tourism a key issue, being the adaptation to such changes one of the main challenges that some mountain areas will have to face in the next few decades (IPCC 2014; UNWTO-UNEP; 2003; Saurí and Llurdés, 2010). In this line, several governmental and intergovernmental reports have pointed out the fragility of winter tourism in different regions around the world to the projected changes on the temporality and availability of snow. These changes could have a significant social an economical impact resulting in a decrease on the viability and sustainability of winter activities, such as the ski industry (ACACIA, 2000; UNWTO-UNEP, 2003; UNWTO-UNEP-WMO, 2008; IPCC, 2013; Saurí and Llurdés, 2010). Moreover, this industry has also been identified as one of the least prepared industries to deal with the climate change impacts (Scott, 2012).

In the late 1980's and 1990's, after a succession of winters with poor snow conditions, the firsts academic studies came out dealing with the climate change impacts on the ski industry. Since then, most of the winter tourism regions of the world have been analyzed, such as the European Alps (Abegg et al., 1996; Breiling & Charamza, 1999; Chaix, 2010; Elsasser & Bürki, 2002; König & Abegg, 1997; Steiger, 2010, 2011, 2012; Steiger & Mayer, 2008; Uhlmann et al., 2009; Endler and Matzarakis, 2011; Balbi et al., 2012), Canada (Lamothe & Périard, 1988; McBoyle & Wall, 1987; Scott et al., 2003, 2006, 2007; Shih et al., 2009), USA (Dawson & Scott, 2007, 2010; Dawson et al., 2009; Lipski & McBoyle, 1991; Scott et al., 2008), Sweden (Moen & Fredman, 2007), Australia (Galloway, 1988; Hennessy et al., 2003, 2009, 2011; Bicknell & McManus, 2006), Japan (Fukushima et al., 2002) or New Zealand (Hendrikx & Hreinsson, 2012). Some of these studies, mostly focused on the supply-side impacts (ski operations), only modeling the natural snowpack at ski resorts (Uhlmann et al., 2009) or applying indicators that are not enough relevant to ski-area operations such as snow cover days, defined as 2,5 cm of snow (Lamothe & Périard, 1988), when in fact ski operators require 30-100 cm of snow to open a ski run. The only exceptions are a few studies using statistical relationships between snow depth and other climatological parameters (Moen and Fredmand, 2007; Galloway, 1988), most of them basing their estimations on physical snow models. One of the major limitations of these studies using statistical models is the omission of the effect of snowmaking on future natural snowpack. This limitation, not only found in statistical models but also in many other studies using physical snow models, is the main drawback found in most of the previous literature analyzing the vulnerability of ski resorts (Scott et al., 2012). This is a key point since these models cannot reflect the current operating realities of many ski resorts around the world. Nowadays snowmaking covers and supplies huge areas of ski resorts and the percentage of snow-machine covered runs increases every year (Steiger, 2008). The studies incorporating this issue (Scott et al., 2003, 2007, 2008, 2011; Hennessy et al., 2008; Steiger, 2010, 2011) found that the impacts on the different regions analyzed are lower than the impacts reported in previous studies considering only natural snow. Finally an alternative approach to the statistical and physical models to analyze the climate change impacts on the ski industry is the analogue approach. Temporal analogues use past and present experiences and responses to climatic variability, change and extremes to provide insight for vulnerability to future climate change (Ford et al., 2010). So far, this approach has been applied in a few studies in North America (Scott, 2006; Dawson et al., 2009, 2001) and one in the Austrian region of Tyrol (Steiger, 2011).

Even though most of the studies are focused on the supply-side of ski industry, there is considerable evidence demonstrating the intrinsic importance of weather and climate for tourist decision-making, including motivations, destination choice and timing of travel, as well as experience (Scott & Lemieux, 2010). Changes in the spatial and temporal distribution of climate resources will have important consequences for tourism demand at various scales (Scott et al., 2012). One of the first studies analyzing the demand response of tourists to climate change (König, 1998) was based on a survey at Australian ski resorts. Respondents were confronted with a scenario in which ''the next five winters would have very little natural snow''. This survey was repeated by Pickering, et al. (2010), and the same scenario was also used in Switzerland by Behringer et al. (2000). Unbehaun, et al. (2008) also analyzed the tourist response to 'several consecutive years of snow deficiency'. Steiger's (2011) analyzed the impact of the record warm winter of 2006-07 in the Austrian Tyrol, finding that the number of skiers significantly decreased. Other studies (Dawson, et al., 2013; 2011; 2009) also show limited variation between responses during past conditions (observed behavior) and future seasons (stated behavior), indicating that behavioral adaptation to future climate change may be similar to what has been observed in recent analogously warm winter seasons (Scott et al., 2012). Although such studies raise the question of how 'very little snow' is to be interpreted, all of them point out that behavioral adaptation of tourists due to spatial, temporal and activity substitution when poor snow conditions, could exert a strong influence on the final output of the climate change impact assessments.

In spite of these limitations, and the heterogeneity of approaches used to analyze the climate change impacts on winter tourism, most of these studies are congruent indicating that climate change will lead to impacts such as ski season length reductions, loss of skiable areas and drop of visitors, both in low altitude and low latitude ski resorts. In this sense, from an operations perspective, the ski tourism industry is at risk due to the decreasing reliability of natural snow cover, the increasing shortening and variability of snow/ski seasons, the increasing need of snowmaking production to ensure a reliable season, and the decreasing snowmaking opportunities due to increasing marginal temperature conditions and costs to efficiently produce snow (Scott et al., 2012).

1.6 Research goal and objectives

In this context, even though the Pyrenees is the most important winter tourism region in Europe after the Alps and the expected shortening of the ski season and the reduction of the available snow, so far there is no academic research analyzing in detail the vulnerability of the Pyrenean ski industry to climate change. Due to this research gap it is not accurately known how climate change could affect the ski industry and which would be the most suitable adaptation strategies for this specific region and particularly for each ski resort (Saurí and Llurdés, 2010).

The answer to these questions will be an essential factor in order to carry out a suitable sustainable future planning in the Pyrenees, not only of the ski industry but also of the current development model of this region. Even though the ski industry has led to an uneven regional development and economic impact as well as environmental impacts due to the marginalization of the primary sector (Lasanta et al., 2007, 2007b), this region is highly dependent on winter tourism industry being their residents well aware that climate change is presented as a future threat to snow availability and to future development of winter tourism related activities (March et al., 2014).

The main goal of this study is to assess how climate change could affect the snowpack depth and duration in the Pyrenees and the potential effects on the ski industry of this region. Based on the results, this study analyzes the suitability and sustainability of the adaptation techniques and strategies to offset the climate variability in the Pyrenees.

1.7 References

Abegg B (1996). *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. vdf Zurich, Zurich.

Abegg B, Agrawala S, Crick F, de Montfalcon A (2007). *Climate change impacts and adaptation in winter tourism*. In: Climate change in the European Alps: adapting winter tourism and natural hazards management. Paris: Organization for Economic Co-operation and Development.

ACACIA (2000). *Tourism and recreation*. In: Parry M (ed) Assessment of potential effects and adaptations for climate change in Europe. Jackson Environment Institute, University of East Anglia, Norwich.

Adam, J.C., Hamlet, A.F., Lettenmaier, D.P.: 2009. Implications of global climate change for snowmelt hydrology in the 21st century. *Hydrological Processes*, 23: 962-972.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P.: 2005 Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438:303–309.

Barrera-Escoda, A., Cunillera, J. (2011) Projeccions de canvi climàtic per a Catalunya (NE Península Ibèrica). Part I: Modelització climàtica regional. Tethys, 8, pp. 77-89, doi: 10.3369/tethys.2011.8.08.

Becker, A. and Bugmann, H. (eds.) (1997). *Predicting Global Change Impacts on Mountain Hydrology and Ecology: Integrated Catchment Hydrology/Altitudinal Gradient Studies*, IGBP Report 43, Stockholm.

Behringer, J., Buerki, R., & Fuhrer, J. (2000). Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. *Integrated assessment*, 1, 331–338.

Beniston, M., (2003). Climatic change in mountain regions: a review of possible impacts. *Climatic Change* 59, 5-31.

Beniston, M., Keller, F., Koffi, B., Goyette, S. (2003b) Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions. *Theoretical and Applied Climatology*, 76: 125-140.

Beniston, M., 2004: Climatic change and its impacts. An overview focusing on Switzerland. Kluwer Academic Publishers, Dordrecht/The Netherlands and Boston/USA, 296 pp.

Bigano, A., Hamilton, J.M. and Toll, R. (2006). The impact of climate change on holiday destination choice. *Climatic Change,* 76: 389-406-

Blanc, C., (2008). Ski resorts in 2020: How to face the future? 5th World Congress on Snow and Mountain Tourism, Andorra.

Bosello, F., Marazzi, L., & Nunes, P. A. L. D. (2007a). *Le Alpi italiane e il cambiamento climatico: Elementi di vulnerabilità ambientale ed economica e possibili strategie di adattamento*. CMCC/APAT.

Breiling, M., Charamza, P., (1999). The impact of global warming on winter tourism and skiing: a regionalised model for Austrian snow conditions. *Regional Environmental Change* 1 (1), 4–14.

Brown, R. D., and P. W. Mote (2009) The response of Northern Hemisphere snow cover to a changing climate. *J. Clim*., 22, 2124–2145.

Brown, R. D., and D. A. Robinson (2011) Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *Cryosphere,* 5, 219–229.

Brunet, M., Casado, M.J, de Castro, M., Galán, P., López, J. A., Martín, J.M., Pastor, A., Petisco, E., Ramos, P., Ribalaygua, J., Rodríguez, E., Sanz, I., Torres, L. (2009). *Generación de escenarios regionalizados de cambio climático para España*. Madrid, Ministerio de Medio Ambiente y Medio Rural y Marino; Agencia Estatal de Meteorología. 158 pp.

Bürki,R., Elsasser,H., Abegg, B, (2003). Climate change and Winter Sports: Environmental and Economic Threats. *5th World Conference on Sport and Environment,* Torino. 2003.

Burki, R., Elsasser, H., Abegg, B., König, U., (2005). Climate change and tourism in the Swiss Alps, In: eds., HallM. and Higham *J. Aspects of Tourism. Tourism, recreation and climate change*,pp. 155-163.

Casola, J.H., Cuo, L., Livneh, B., Lettenmaier, D.P., Soelinga M.T., Mote P.W., Wallace J.: 2009. Assessing the impacts of global warming on snowpack in the Washington Cascades. *Journal of Climate*, 22: 2758-2772.

CIPRA, Commission Internationale pour la Protection des Alpes, (2003). *Aufrüstung im Alpinen Wintersport : ein Hintergrundbericht*. Disponible a :http://www.alpmedia.net.

Clarimont, S., (2008). Turismo de invierno y cambio climático: la producción de nieve artificial en los Pirineos, ¿un uso sostenible del agua?. *6° Congreso Ibérico sobre Gestión y Planificación del Agua*, Vitoria, Federación Nueva Cultura del Agua - Universidad del País Vasco.

Daly, H.E, Cobb, J.B. (1990) *For the Common Good*, London: Green Print.

Dawson, J., Scott, D., & McBoyle, G. (2009). Analogue analysis of climate change vulnerability in the US northeast ski tourism. *Climate Research*, 39, 1–9.

Dawson, J., Havitz, M., & Scott, D. (2011). The influence of ego involvement on climate-induced substitution and place loyalty among alpine skiers. *Journal of Travel and Tourism Marketing*, 28, 388–404.

Dawson, J., Scott, D. (2012) Managing for Climate Change in the Alpine Ski Sector. *Tourism Management*. 35, 244-254.

Dawson, J., Scott, D., Havitz, M. 2013. Skier demand and behavioural adaptation to climate change in the US Northeast. *Leisure/ Loisir*, 37(2), 127-143.

Deadman P, Robinson D T, Moran E, Brondizio E, (2004). Colonist household decisionmaking and land-use change in the Amazon Rainforest: an agent-based Simulation. *Environment and Planning B - Planning and Design* 31, 693-709.

Déry, S. J., and R. D. Brown, (2007) Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback. *Geophys. Res. Lett.,* 34, 6 (L22504).

Diaz, H.F., Eischeid, J.K. (2007). Disappearing “alpine tundra” Köppen climatic type in the western United States. *Geophysical Research Letter*, (34): L18707.
Ecoplan/Sigmaplan (2007). *Auswirkungen der Klimaänderung auf die Schweizer Volkswirtschaft (nationale Einflüsse).* Auftraggeber Bundesamt für Umwelt (BAFU) und Bundesamt für Energie (BFE).

Dresner, S. (2002). *The principles of Sustainability*. Erthscan.

EEA, European Environment Agency, (2009). *Regional Climate Change and Adaptation*. Copenhague.

Elsasser H, Bürki R (2002). Climate change as a threat to tourism in the Alps. *Climate Research* 20, 253-257.

Endler C, Matzarakis A. 2011. Climatic potential for tourism in the Black Forest, Germany-Winter season. *International Journal of Biometeorology* 55:339-351.

ESCAT, *Generació d’escenaris climàtics amb alta resolució per a Catalunya (Resum executiu)*. (2012). Servei Meteorològic de Catalunya. Departament de Territori i Sostenibilitat. Generalitat de Catalunya.

Esteban P., Prohom Duran M., Aguilar E., (2012) Tendencias recientes e índices de cambio climático de la temperatura y la precipitación en Andorra, *Pirineos* (1935-2008). Pirineos 167.

Etchevers P, Martin E., (2002*). Impact d’un changement climatique sur le manteau neigeux et l’hydrologie des bassins versants de montagne*. International Meeting “L’eau en montagne”, Mégève, 8.

Finger, D., G. Heinrich, A. Gobiet, 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.

Fitzharris, B. B., Allison, I., Braithwaite, R. J., Brown, J., Foehn, P., Haeberli, W., Higuchi, K., Kotlyakov, V. M., Prowse, T. D., Rinaldi, C. A., Wadhams, P., Woo, M. K., and Youyu Xie, (1996). *The Cryosphere: Changes and their Impacts, in Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* Chapter 5, Cambridge University Press, pp. 241–265.

Föhn, P., (1990). Schnee und Lawinen. In: *Schnee, Eis und Wasser der Alpen in einer wärmeren Atmosphäre*, Internationale Fachtagung, Mitteilungen VAW ETH Zurich 108, 33-48.

Ford, J.D., Keskitalo, E.C.h:, Smith, T., Pearce, T., Berrang-Ford, L., Duerden., F. and Smit, B. (2010). Case study and analogue methodologies in climate change vulnerability research. *WIRE's Climate Change,* 1(3):374-392.

Fukushima T., Kureha M., Ozaki N. et al. (2002). Influences of air temperature change on leisure industries: case study on ski activities. *Mitigation and Strategies for Climate Change* 7, 173-189

Galloway, R., (1988). The potential impact of climate change on Australian ski fields. In Pearman G (ed) *Greenhouse: planning for climatic change*. CSIRO, Melbourne.

Ganguly, A.R., Steinhaeuser, K., Erickson, D.J., Branstetter, M., Parish, E.S., Singh, N., Drake, J.B., Buja, L.: 2009. Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves. *PNAS*, 106 (37): 15555-15559.

García-Ruiz, J.M., López-Moreno, J.I. Serrano-Vicente S.,M, Beguería, S., Lasanta, T.: 2011. Mediterranean water resources in a global change scenario. *Earth Science Reviews*, 105 (3-4): 121-139.

Gesellschaft für ökologische Forschung. Base de dades de fotografies que documenten l'evolució de les glaceres als Alps, http://www.oekologische-forschung.de/, last access: march 2014.

Gössling, S., Scott, D., Hall,C.M., Ceron, J.P, Dubois, G. (2012). Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, 39(1),36-58.

Grabherr, G., Gottfried, M., and Pauli, H. (1994). Climate Effects on Mountain Plants, *Nature* 369, 448.

Haeberli, W., Noetzli, J., Zemp, M., Baumann, S., Frauenfelder R. and Hoelzle, M. (2005). *Glacier Mass Balance Bulletin* No. 8, 2002–2003. IUGG(CCS)–UNEP–UNESCO–WMO, Zurich

Hahn, F., (2004). L'enneigement artificiel dans l'arc alpin : Rapport de synthèses. CIPRA Internationale Alpenschutzkommission. Disponible a www.cipra.org.

Hamilton L, Rohall D, Brown B et al (2003). Warming winters and New Hampshire's lost ski areas: an integrated case study. *International Journal of Sociology and Social Policy* 23(10), 52-73.

Hamilton, L, Brown, C., & Keim, B. D. (2007). Ski areas, weather and climate: Time series models for New England case studies. International Journal of Climatology, 27, 2213–2124.

Hansen-Bristow, K. J., Ives, J. D., and Wilson, J. P. (1988), 'Climatic Variability and Tree Response within the Forest-Alpine Tundra Ecotone', *Annals of the Association of American Geographers* 78, 505–519.

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

Hennessy, K., Whetton, P.H., Walsh, K., Smith, I.N., Batholts, J.M., Hutchinson, M. and Sharpies, J. (2008). Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snow making. Climate *Research,* 35:255-270.

Heo, I., and Lee, S., (2008). The Impact of Climate Changes on Ski Industries in South Korea – In the case of the Yongpyong Ski resort. *Journal of the Korean geographical society* 43 (5),715-727.

Holzhauser, H.P. and Zumbühl, H.J. (2003). Nacheiszeitliche Gletscherschwankungen. Sonderdruck zum 54. Geographentag Bern, *Hydrologischer Atlas der Schweiz,* Tafel 3.8
Huntley, B., (1991). How Plants Respond to Climate Change: Migration Rates, Individualism and the Consequences for Plant Communities', *Ann. Botany* 67, 15–22

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

Intergovernmental Panel on Climate Change IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Intergovernmental Panel on Climate Change IPCC (2013). *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Intergovernmental Panel on Climate Change IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R.

Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, XXX pp.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Wolff, E. W. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. *science*, *317*(5839), 793-796.

Keller, F., Kienast, F., and Beniston, M. (2000). Evidence of the Response of Vegetation to Environmental Change at High Elevation Sites in the Swiss Alps. *Regional Env. Change* 2, 70–77

König, U., (1998). *Tourism in a warmer world: implications of climate change due to enhanced greenhouse effect for the ski industry in the Australian Alps.* Wirtschaftsgeographie und Raumplanung 28 University of Zurich

König, U., Abegg, B. (1997). Impacts of climate change on tourism in the Swiss Alps. *Journal of Sustainable Tourism* 5(1), 46-58

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

Lasanta, T., Laguna Marín-Yaseli, M., Vicente-Serrano, S.M. (2007). Do tourism-based ski resorts contribute to the homogeneous development of the Mediterranean mountains? A case study in the Central Spanish Pyrenees. *Tourism Management*, 28(5): 1326-1339.

Lasanta, T., Laguna Marín-Yaseli, M., Vicente-Serrano, S.M. (2007b). Variabilidad especial de los efectos socioeconómicos de las explotaciones de esquí alpino en los municipios rurales del Pirineo aragonés. *Pirineos* 162: 155-176.

Lavaud, J., (2008). *L'impact du changement climatique en Midi-Pyrénées, Exemple de la chaîne des Pyrénées*. l'Agence Régionale Pour l'Environnement de Midi-Pyrénées.

Ligmann-Zielinska, A, Jankowski, P. (2007). Agent-based models as laboratories for spatially explicit planning policies, *Environment and Planning B*: 34(2), 316-335

Lipski S., McBoyle G., (1991). The impact of global warming on downhill skiing in Michigan. *East Lakes Geographer* 26: 37-51

López-Moreno JI, Serrano-Vicente SM. 2007. Atmospheric circulation influence on the interannual variability of snowpack in the Spanish Pyrenees during the second half of the twentieth century. *Nordic Hydrology* 38 (1):38-44.

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

López-Moreno JI, Goyette S, Beniston M. (2008b). Climate change prediction over complex areas: spatial variability of uncertainties and expected changes over the Pyrenees from a set of regional climate models. *International Journal of Climatology* 28 (11):1535-1550.

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

López-Moreno, J.I., Pomeroy, J., Revuelto, J., Vicente-Serrano, S.M.: (2013). Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. *Hydrological Processes*. 27(18): 2637-2650

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J. M., Siegenthaler, U., Stocker, T. F. (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, *453*(7193), 379-382.

March, H., Saurí, D., Llurdés, J.C. 2014. Perceptions on the effects of climate change in winter and summer tourists areas: The Pyrenees and the Catalan and Balearic coasts, Spain. *Regional Environmental Change*, 14(3), 1189-1201.

Martin, E. and Durand, Y. (1998), Precipitation and Snow Cover Variability in the French Alps, in: Beniston, M. and Innes, J. L. (eds.), *The Impacts of Climate Change on Forests*, Springer-Verlag,Heidelberg/New York, pp. 81–92.

Meadows, D.H., Randers, J. and Meadows, D.L. (2004) *Limits to Growth: The 30- Year Update*. White River Junction, Vermont: Chelsea Green Publishing Co.

Meier, R., (1998). *Sozioökonomische Aspekte von Klimaänderungen und Naturkatastrophen in der Schweiz* (Projektschlussbericht NFP 31). Zurich: Vdf Hochschulverlag

Messerli B, Ives JD. (eds) .1997. *Mountains of the World. A global priority*. The Parthenon Publishing Group, London, 495 pp.

Milankovitch, M., 1998. *Canon of Insolation and the Ice Age Problem*. Belgrade: Zavod za Udzˇbenike i Nastavna Sredstva.

Minder, J.R.: 2010. The sensitivity of mountain snowpack accumulation to climate warming. *Journal of Climate*, 23, 2634–2650

Moen, J., Fredman, P. (2007). Effects of climate change on alpine skiing in Sweden. Journal of sustainable tourism 15: 418-437.

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

OPCC. Observatoire Pyrénéem du changement climatique. http://www.opcc-ctp.org
Last access 21/2/2014.

Ohmura, A. 2012. Enhanced temperature variability in high-altitude climate change. *Theoretical and Applied Climatology*, 10 (4): 499-508.

Ozenda, P. and J.-L. Borel (1991), Les Conséquences Ecologiques Possibles des Changements Climatiques dans l'Arc Alpin, Rapport Futuralp No. 1, International Centre for Alpine Environment (ICALP), Le Bourget-du-lac, France

Pepin, N.C., Seidel, D.J. 2005. A global comparison of surface and free-air temperatures at high elevations. *Journal of Geophysical Research*, 110: D03104.

Pepin, N. C., Lundquist, J.D.: 2008. Temperature trends at high elevations: Patterns across the globe. *Geophys. Res. Lett.*, 35: L14701.

Peters, R. L. and Darling, J. D. S. (1985). The Greenhouse Effect and Nature Reserves: Global WarmingWould Diminish Biological Diversity by Causing Extinctions among Reserve Species, *Bioscience* 35, 707–717.

Pickering, C. M., Castley, J. G., & Burtt, M. (2010). Skiing less often in a warmer world: Attitudes of tourists to climate change in an Australian ski resort. *Geographical Research*, 48, 137–147.

Planton, S., (2008). Le changement climatique: de la planète à la région Midi-Pyrénées Météo-France, CNRM/GAME

Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover E. (2012) Modeling climate change effects on winter ski tourism in Andorra. *Clim Res* 54:197-207

Pons M., López-Moreno, J.I., Esteban, P., Macià, S., Gavaldà, J., García, C., Rosas-Casals, M., Jover, E. (in press). Influencia del cambio climático en el turismo de nieve del Pirineo. Experiencia del proyecto de investigación NIVOPYR de la comunidad de trabajo de los Pirineos (CTP). *Pirineos,* 169.

Price, M. F., (1990). Temperate Mountain Forests: Common-Pool Resources with Changing, Multiple Outputs for Changing Communities. *Natural Resources Journal* 30, 685–707.

Railsback, S.F., (2001). Concepts from complex adaptive systems as a framework for individual-based modelling. *Ecol. Model.* 139, 47–62

Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson , G.M., Shepherd, A. (2008) Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, 349: 397–410.

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

SCAMPEI (2012). Scénarios climatiques adaptés aux zones de motagnes: Phénomènes extrêmes, enneigement et inCertitudes. http://www.cnrm.meteo.fr/scampei/

Scholl, H. J., (2001). Agent-based and systems dynamics modeling: A call for cross study and joint research. *34th Hawaiian International Conference on System Sciences*, Maui, HI.

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. *Climate Research*, 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. *Journal of Sustainable Tourism*, 14(4), 376–398

Scott, D., McBoyle, G., Minogue, A. (2007). The implications of climate change for the Québec ski industry. *Global Environmental Change*, 1, 181–190

Scott, D., McBoyle, G. (2007). Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies to Global Change*, 12(8), 1411–1431

Scott D., Dawson, J., Jones, B. (2008). Climate change vulnerability of the US Northeast winter recreation-Tourism sector. *Mitigation Adaptation Strategies for Global Change*,13, 577–596

Scott, D., & Lemieux, C. (2010). Weather and climate information for tourism. *Proceedia Environmental Sciences*, 1, 146–183.

Scott, D., Lemieux, C., Kirchoff, D. and Milnik, M. (2011). *Analysis of socioeconomic impacts and adaptation to climate change by Wuébec's Tourism industry. Technical report 1: Climate Change Impact Assessment: Risks and opportunities*. Waterloo, Ontario/Montréal, Québec, Canada: Interdisciplinary Center onClimate Change (IC3), University of Waterloo and Consortium on Regional Climatology and Adaptation to Climate Change (OURANOS).

Scott, D., Gössling, S., Hall, C.M. (2012) Climate Change and Tourism: Impacts, Adaptation and Mitigation. London: Routledge. 423 pgs.

Shih, C., Nicholls, S., & Holecek, D. F. (2009). Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research*, 47(3), 359–372

Smajgl, A., Brown, D. G., Valbuena, d., and Huigen, M. G. A. (2011). Empirical characterisation agent behaviours in socio-ecological systems. *Environmental Modelling and Software* 26, 837-844

Shih, C., Nicholls, S., Holecek, D.F. (2009). Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research* 47(3):359-372

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

Steiger, R. (2010). The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Climate Research, 43(3),* 251-262

Steiger, R. (2011). The impact of snow scarcity on tourism. An analysis if the record warm seson 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. *Journal of Sustainable Tourism*, 20(6), p. 867–882

Tague, C., Dugger, A.L.: 2010. Ecohydrology and Climate Change in the Mountains of the Western USA - A Review of Research and Opportunities. *Geography Compass*, 4 (11): 1648 - 1663
Trujillo, E., Molotch, N.P., Goulden, M.L., Kelly, A.E., Bales, R.C.: 2012. Elevation-dependent influence of snow accumulation on forest greening. *Nature Geoscience*, 5: 705-709.

Turner, B.L., Clarck, W.C., Kates, R.W., Richards, J.F, Mathews, J.Y, W.B. (eds) (1990) The Earth as Trasnformed by Human Action. Cambridge: Cambridge University Press.

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. *International Journal of Climatology* 29, 1048–1055.

Unbehaun, W., Probstl, U., & Haider, W. (2008). Trends in winter sport tourism: Challenges for the future. *Tourism Review*, 63, 36–47.

UNWTO-UNEP (2003) Climate change and tourism. Proceedings of the First International Conference on Climate change and Tourism, Djerba, 9-11 April. Madrid: World Tourism Organization.

UNWTO-UNEP-WMO (2008). Climate change and tourism: Responding to global challenges. (prepared by Scott, D., Amelung, B., Becken, S., Ceron, J. P., Dubois, G., Gössling, S., Peeters, P. and Simpson, M. C.), Madrid and Paris: UNWTO.WCED (1987) Our Common Future (The Brundtland Report). Oxford: OXford University Press/ World Comission on Environment and Development.

Weart, S. R. (2003) The Discovery of Global Warming. Cambridge, MA: Harvard University Press.

Whiteman,D. (2000). Mountain Meteorology, Oxford University Press, 355 pp.

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

Zemp, M., Frauenfelder, R., Haeberli, W. and Hoelzle, M. (2005). Worldwide glacier mass balance measurements: General trends and first results of the extraordinary year 2003 in Central Europe. *Data of Glaciological Studies*, 99, 3–12

Zemp, M., Haeberli, W., Hoelzyle, M., Paul, F. (2006). Alpine glaciers to disappear within decades? *Geophysical Research Letters*, Vol. 33, L13504

2. The vulnerability to climate change of the Pyrenean ski resorts

Chasing angels or fleeing demons,
go to the mountains.

Jeffrey Rasley
Bringing Progress to Paradise

2.1 The Pyrenees and its snow tourism

The Pyrenees is an approximately 450 km long mountain range comprising the northern part of Spain, the southern part of France and the small country of Andorra (Figure 2.1). Altitude ranges from 300 m to more than 3000 m a.s.l. The climate of the Pyrenees is subject to an eastward transition from Atlantic to Mediterranean conditions. Moreover, macro-relief introduces a significant variability to the distributions of precipitation and temperature. The Foehn effect is frequently observed in the area, wet air masses are lifted up in northern slopes leading to drier and warmer conditions southward, significantly enhancing the differences in precipitation between the northern and southern slopes, and leading to higher temperatures on the southern side. In the mountains, annual precipitation exceeds 600 mm, reaching 2000 mm at the highest divides. Most of the annual precipitation falls during the cold season (December–March) in the Atlantic areas and during spring and autumn (April–June and September–November, respectively) in the Mediterranean regions. Summers are generally relatively dry in the Pyrenees (López-Moreno et al., 2009). Based on García-Ruiz et al. (1986) and López-Moreno (2006) the thermal altitudinal gradient for the Pyrenees is around 0.63°C/100 m. Based on these gradients, the annual 0°C isotherm is confined to around 2900 m (Chueca-Cía et al., 2003). Between November and April, the 0°C isotherm is located at approximately 1600–1700 m a.s.l. (García-Ruiz et al., 1986), representing the level above which snow accumulates during these months.

Figure 2.1. Topographic map of the Pyrenees. Source: NASA Shuttle Radar Topography Mission, NGDC ETOPO1 .

The Pyrenees is one of the most important winter tourism regions in Europe after the Alps. Among all the winter activities, alpine ski is the most important one in this regions in terms of visitors and revenues. Enclosing 49 alpine ski resorts, this region receives around 11 million of skiers per year (calculated average of the seasons 2009-2010 to 2012-2013) being Grandvalira, Baqueira Beret, Vallnord, Domaine du Tourmalet and Formigal the 5 resorts with more kilometers of runs (Figure 2.2) and the highest skier attendance during the last 5 years (Figure 2.3).

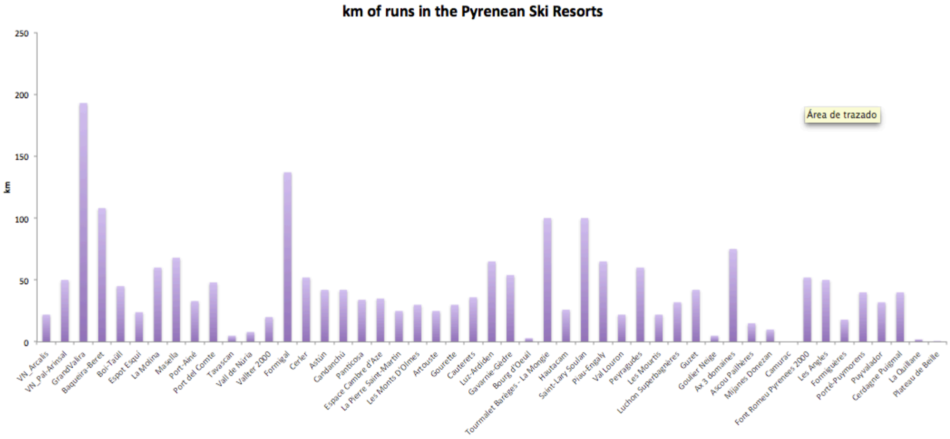


Figure 2.2. Kilometers of runs in the Pyrenean ski resorts

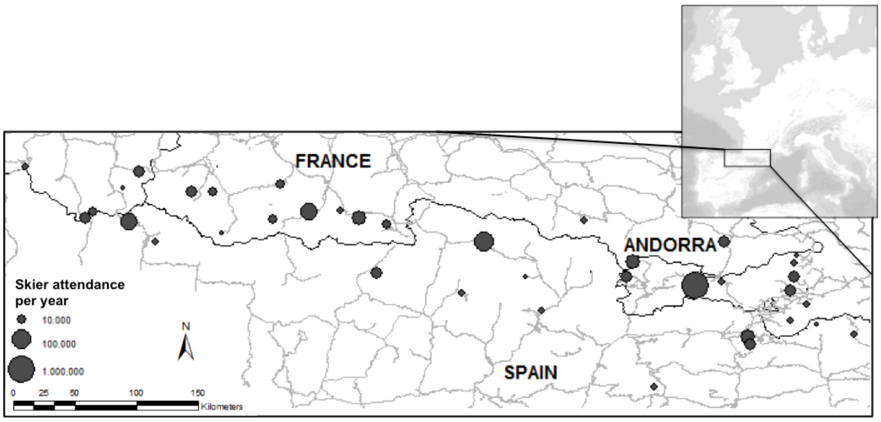


Figure 2.3. Ski resorts of the Pyrenees. Bullets represent the average skier attendance at each ski resort from 2009-2010 to 2012-2013.

The elevation of the Pyrenean ski resort ranges from 1350 to 2700 m. a.s.l. with an average mean elevation around 1950 m a.s.l. (Figure 2.4).

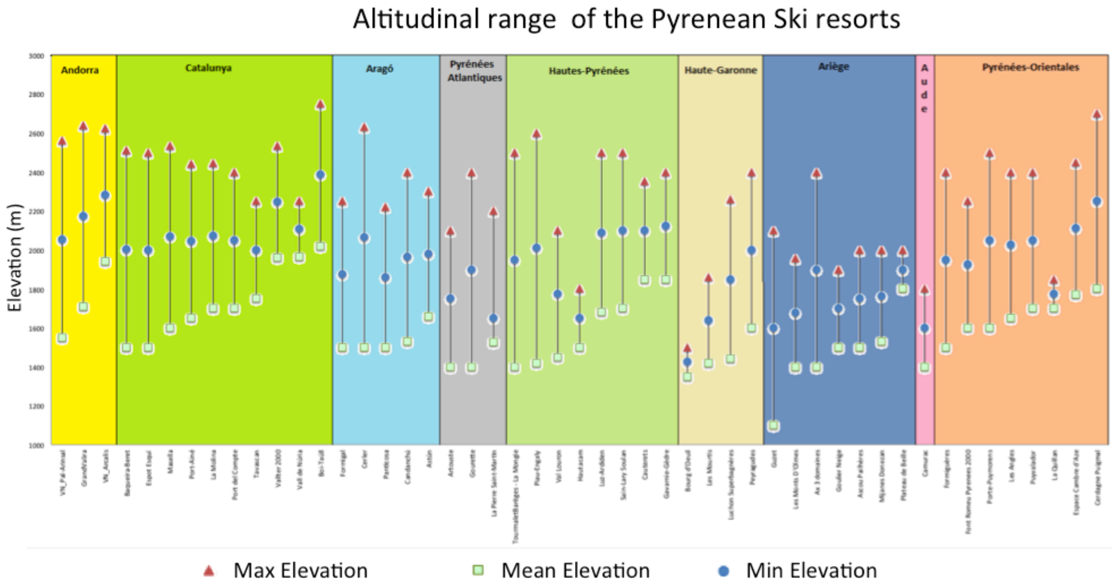


Figure 2.4. Altitudinal range of the Pyrenean ski resorts distributed by regions

However, many ski resorts do not follow a linear altitudinal distribution and usually most of their ski areas are concentrated in the highest half of the elevation range. For example, if we have a closer look to the Andorran ski resorts, Pal-Arinsal, with a mean elevation of 2055 m, has most of its ski area between 1900 and 2200 m and in Arcalís and Grandvalira, with a mean elevation of 2283 m and 2175 m respectively, the skiable area is concentrated between 2250 and 2500 (Figure 2.5).

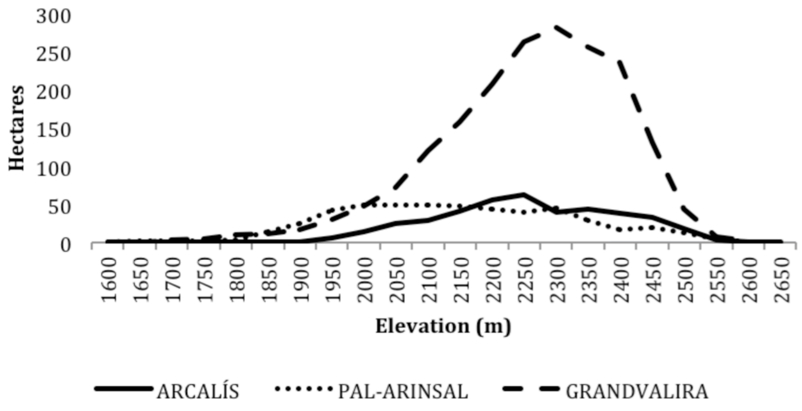


Figure 2.5. Altitudinal distribution of the Andorran ski resorts.

2.2 Climate changes effects on the future snowpack in the Pyrenees ski resorts

Many climate change studies have identified and analyzed the physical impacts and changes on ecosystems. However, the understanding of the relationship between these physical impacts on the environment and their human and social implications, such as socioeconomic impacts or human responses to climate changes, is still one of the main challenges in climate change science. The aim of this study is to relate the projected changes on snow conditions with future average winter season length for each ski resort of the Pyrenees as socioeconomic indicator in three different scenarios: one present scenario and two future scenarios representing a mid and a high climate change. Figure 2.6 shows the conceptual map with the main components of the model. The model includes regional climate change projections in order to simulate the future snowpack in the different ski resorts of the Pyrenees. Furthermore, the model includes a snowmaking module that simulates the effect of snow production systems in the enhancement of snow depth. Since data about small ski resorts of the Pyrenees are not available, 41 of the total 49 ski resorts were analyzed in the present study, representing more than 92% of the total present attendance of skiers in the region (DSF, 2012; Botti, 2013; ATUDEM, 2013; SkiAndorra). The remaining 8 ski resorts are very small ski areas (less than a couple or three of runs and a couple of ski lifts, often presented as s complementary activity of a hotel or nordic ski resort) for which information was not available.

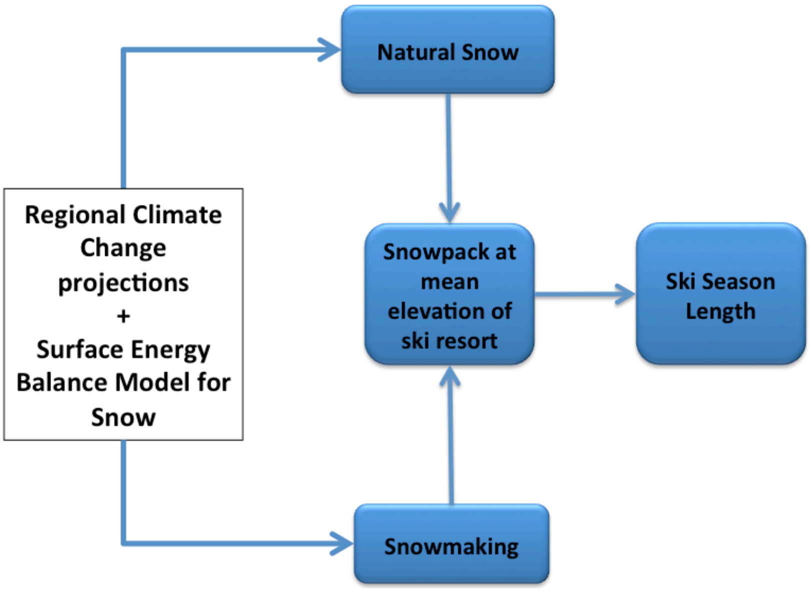


Figure 2.6. Conceptual map of the model linking regional climate change projections to forecast the future snowpack with season length in each ski resort.

2.2.1 Future Natural snowpack changes in the Pyrenean ski resorts

In recent decades a significant increase in temperature has been detected in the majority of the mountain regions around the world accompanied by a shift toward earlier snowmelt and declining snow accumulation (Mote, 2003; Barnett et al., 2005). This change in snowpack dynamics is a consequence of the great sensitivity of snow to temperature increase, which causes a decreasing proportion of snowfall relative to rainfall, and an increase in available energy for snow melting (Rood et al., 2008). Thus, a change of +1°C was reported to cause a 20% reduction in accumulated snow water equivalent, and a noticeable shortening of the snow season in a small basin in the Pyrenees (López-Moreno et al., 2013). Despite the high uncertainties and large regional variability, climate models project that the temperature will continue to increase in coming decades (Ganguly et al., 2009). Mountain areas are expected to be particularly affected by high rates of warming (Nogués-Bravo et al., 2007), with consequent impacts on the accumulation and duration of mountain snowpacks (Adam et al., 2009; Hamlett, 2001; García-Ruiz et al., 2011, López-Moreno et al., 2013). Much research effort has been directed at assessing what environmental and socioeconomic effects a thinner snowpack of shorter duration might have, including on water resources 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., 2011) or the viability of ski resorts (previously cited).

In order to estimate the future natural snow conditions at each ski resort the model uses regional projections of the daily snowpack in the Pyrenees during the 21st Century from López-Moreno et al. (2009). This study simulates the snow depth and the snow duration running the GRENBLS, a Surface Energy Balance Model (Keller et al., 2005) with climatic inputs provided by the HIRHAM Regional Climate Model (Christensen et al., 1998). The seasonal evolution of snowpack is simulated representing average conditions over a surface area typical of a RCM employed during the EU PRUDENCE project, presented in an hourly basis and with a spatial resolution of 50 km2 (Christensen et al., 2002). The Surface Energy Balance Model (SEBM) for snow simulates the evolution of the snowpack based on the thermal fluxes affecting the snow (Figure 2.7).

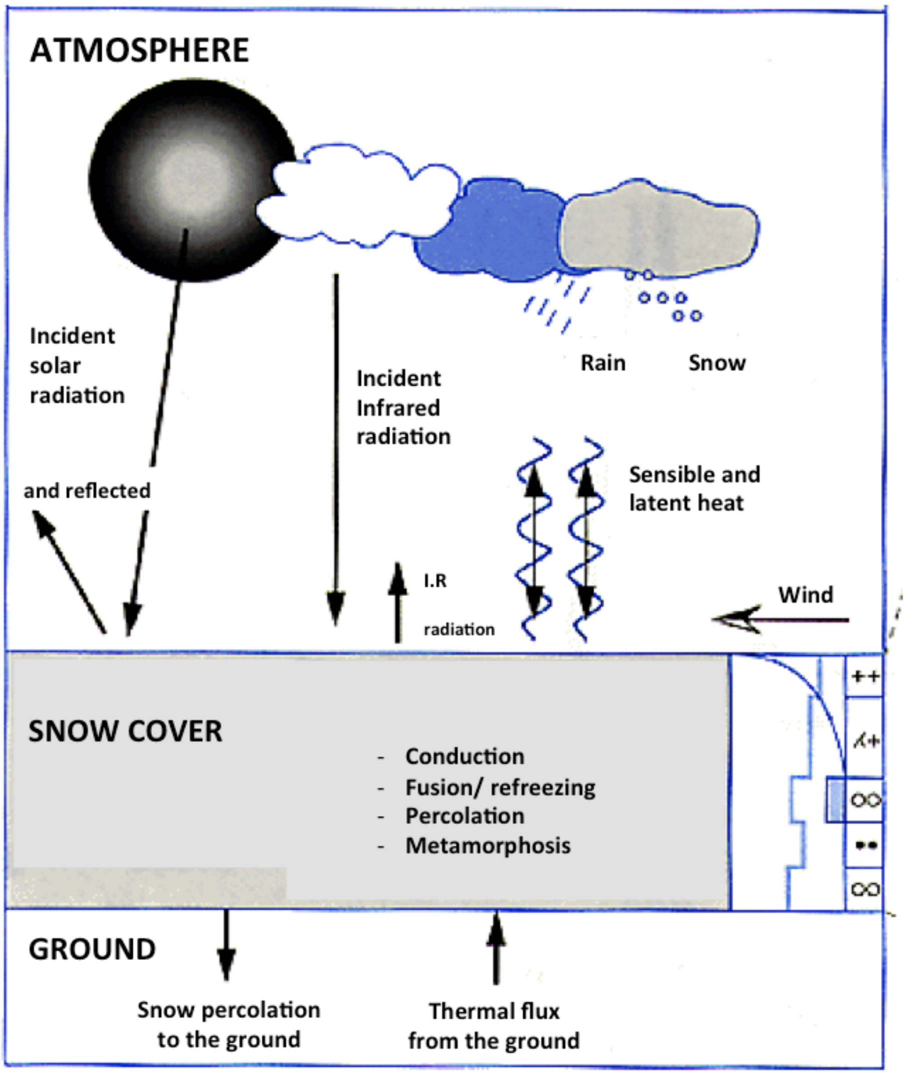


Figure 2.7. Conceptual map of the variables and processes affecting the evolution of the snowpack and the energy fluxes modeled in a Surface Energy Balance Model for Snow. Source: Figure modified from Météo France.

GRENBLS is a single-layer physically-based model driven by hourly input data of air temperature, dew point temperature, anemometer-level wind magnitude, precipitation, surface pressure, and incident solar radiation. The model computes the radiative fluxes from cloudiness data and the surface turbulent sensible and latent fluxes. The bulk heat and moisture transfer coefficients are 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 considers the energy change associated with the melting of frozen soil moisture and snow. The temperature of the snowpack is computed in a prognostic manner 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 directly into the soil in liquid form. Snow is modeled as an evolving one-layer pack characterized by temperature Tsnow (K), mass Msnow (kg/m2), and density qsnow (kg/m3). The surface energy budget is computed over the snow cover at each model time step. The radiative and turbulent fluxes are computed first, followed by heat storage in the snowpack; if the latter value is positive and the snow temperature is below the melting point, the excess energy is 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 has been adopted following the ideas of Verseghy (1991). The snow density of the bulk snow layer increases exponentially with time from the fresh-fallen snow value, qsnow,min = 100 kg/m3, to a maximum of qsnow,max = 300 kg/m3. In a similar manner, changes in snow albedo that accompany snow aging are 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 SRES A2 and B2 (IPCC, 2007) and for different altitudinal levels: 1500, 2000, 2500, and 3000 m a.s.l.. Outputs are Snow Water Equivalent (SWE) and snow depth series at hourly intervals at 20 points of the Pyrenees and at four different altitudinal levels (1500, 2000, 2500 and 3000 m a.s.l.). Between these altitudinal levels, the snow depth has been interpolated in order to simulate the snowpack every 150 m. Observed snow depth at a given location is strongly affected by local conditions (aspect, wind drift processes, etc.), whereas data derived from RCMs reflect the mean conditions of a 50 x 50 km grid cell. To assess the capacity of simulated snowpack with an energy balance model based on HIRHAM data to reproduce Pyrenean snowpack and its spatial distribution, mean daily snow depth recorded at four locations in the 1990s are compared with simulated snow series at the closest grid cells and at the altitudinal plane closest to the location of the observed records. (López-Moreno et al., 2009). The model has been calibrated with a control period and its performance is in good agreement with the overall snow depth and duration of the observed snowpack in the Pyrenees.

Only Formigal presented a significant different behavior with the simulated data. In this case, the snowpack was modeled using the Cold Region Hydrological Model (CRHM; Pomeroy et al., 2007) with historical data from the nearest meteorological station to the ski resort, Izas (López-Moreno et al., 2013; 2013b). The CRHM platform uses a modular modeling object-oriented structure to simulate a comprehensive range of hydrological processes in mountainous and cold regions (including blowing snow, interception, energy balance snowmelt, and infiltration to frozen soils).

The model simulations project that the snowpack in the Pyrenees will be strongly affected by projected climate change, with a marked decrease in snow depth and duration of snowpack. Different greenhouse gas emission scenarios (SRES) lead to significant differences in the severity of expected changes in snowpack, being at least twice as pronounced under the A2 scenario compared with B2. Noticeable spatial differences in the magnitude of simulated changes in snowpack are detected. Snowpack in the central and eastern areas of the Spanish Pyrenees is clearly the most strongly affected by climate change. The impact of climate change on snowpack is highly sensitive to the altitudinal gradient. The decrease in accumulated Snow Water Equivalent (SWE) at 3000 m a.s.l. is just 25% of that simulated at 1500 m. In the latest sectors under SRES A2 and B2, Accumulated SWE is predicted to decrease by up to 78% and 44%, respectively, and the duration of the snowpack by 70% and 32% (figure 2.8).

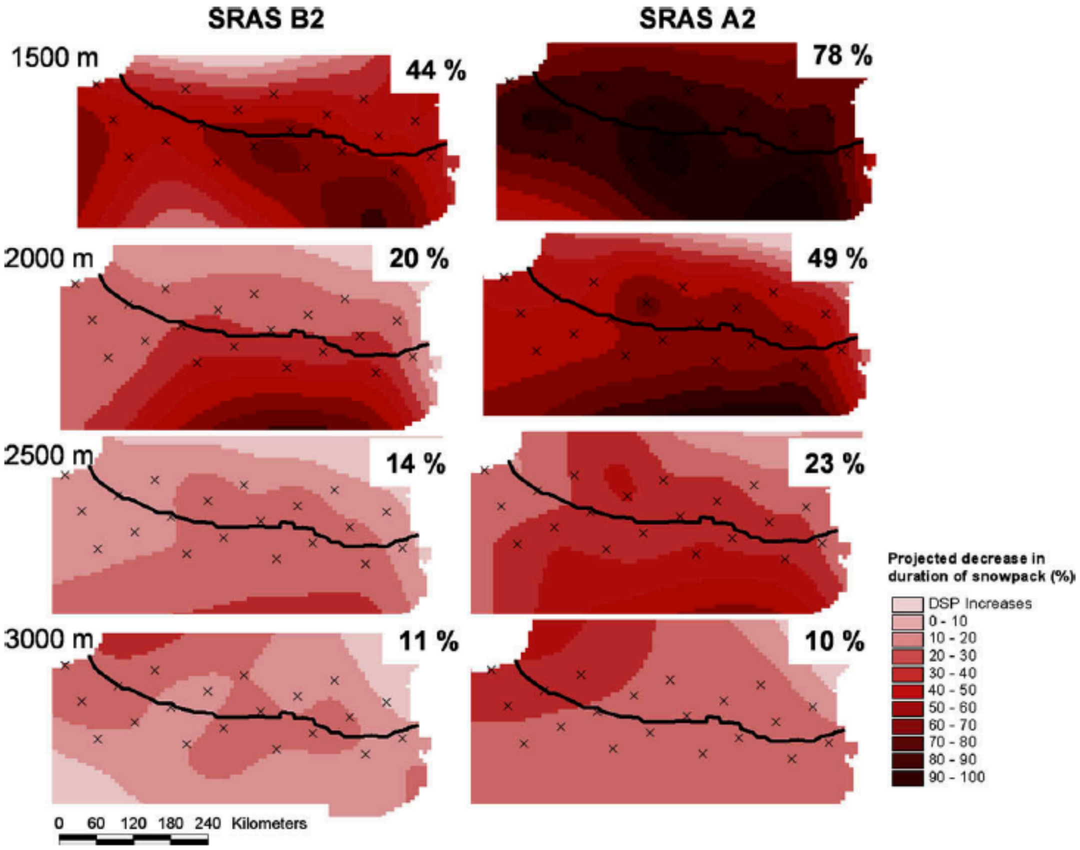


Figure 2.8. Simulated changes in the duration of the snowpack according to climate change projected by the HIRHAM model under SRES B2 (left) and A2 (right) at different altitudinal planes: 1500 m a.s.l. (A), 2000 m (B), 2500 m (C), and 3000 m (D). Source: López-Moreno et al.,2009.

The ski season length has been calculated applying a 30 cm threshold to the natural snowpack projections obtained from the snow model in the mean elevation of each ski resort. Because the altitudinal distribution of all the Pyrenean resorts is not available, the mean elevation is used as an indicator of the average snowpack available at each ski resort (Abegg et al. 2007, Scott et al. 2003, Scott & McBoyle 2007, Steiger 2010). The 30 cm threshold used to assess the future reliability is one of the most used criterions to assess the climate change vulnerability of ski resorts (Witmer, 1986; Abegg, 1996; Scott et al. 2008; Steiger et al. 2010). In order to simulate the ski season length, those days with at least 30 cm of snow depth were those considered as open days. With these data the model computes how many days with minimum snow conditions are achieved to open the resort during a whole winter season. Figure 2.9 shows the mean control period (1961-1990) and future snowpack in the 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 (equivalent to the B2 scenario for the period 2070-2100) and +4°C increase (equivalent to the A2 scenarios for the 2070-2100 period) in winter average temperature.

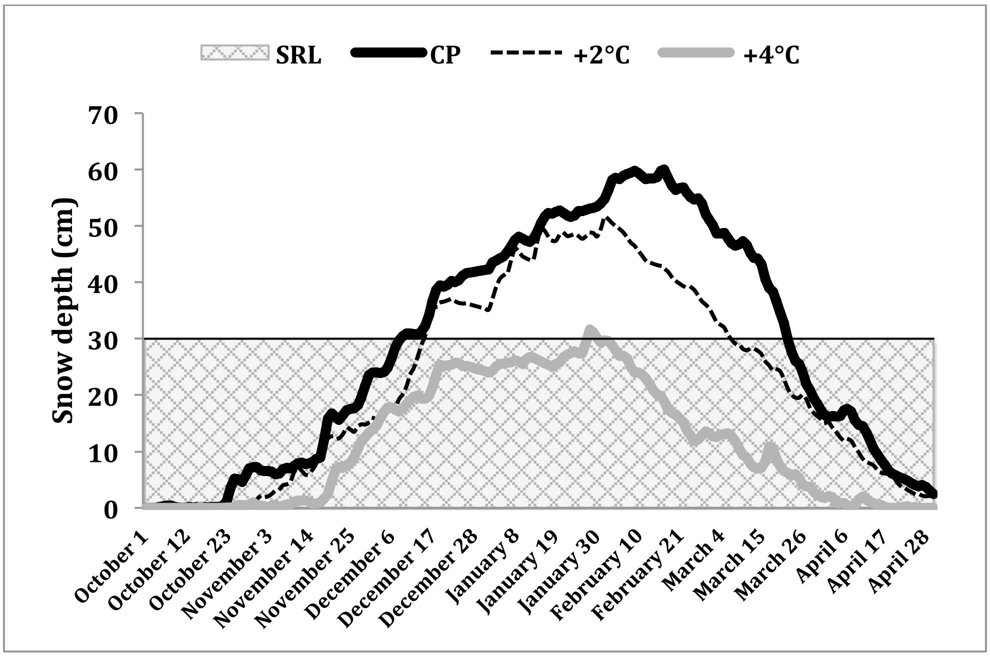


Figure 2.9. Mean control period (CP) and future snowpack (+2°C and +4°C) for Ax 3 Domaines ski resort at 1900 m.

2.2.2 Snowmaking effect on natural snow

Snowmaking is currently the main adaptation strategy to offsetting the natural variability of snow. It helps to guarantee enough snow depth, scheduled openings, and stable revenues but it is also a commercial and image strategy to extend the season with the aim to increase revenues (Steiger & Mayer, 2008). Over the last few decades, ski resorts across the world have invested significant amounts of money in snow production systems and the Pyrenean ski resorts are no exception to this global trend (Saurí and Llurdés, 2010). In this context, the model includes a snowmaking module in order to simulate the effect of the snowmaking systems in the enhancement of the snowpack in order to achieve a more realistic projection of the future ski season length. In this model only the 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 to compute the potential snowmaking days during a winter season. During these potential snowmaking days, it is assumed that 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 following these criteria. Thus, the resulting season length will depend on the natural snow pack available and the potential snow produced by these systems. Figure 2.10 shows the enhancement of the natural snowpack at 1900 m in the Andorran ski resort of Pal following the defined parameters for a +2°C climate change scenario. The figure shows the importance to include this factor in the analysis. The presented resort, when considering natural snow alone would have only a short period with more than 30 cm of snow depth, but when including snowmaking most of the winter season will be above this threshold.

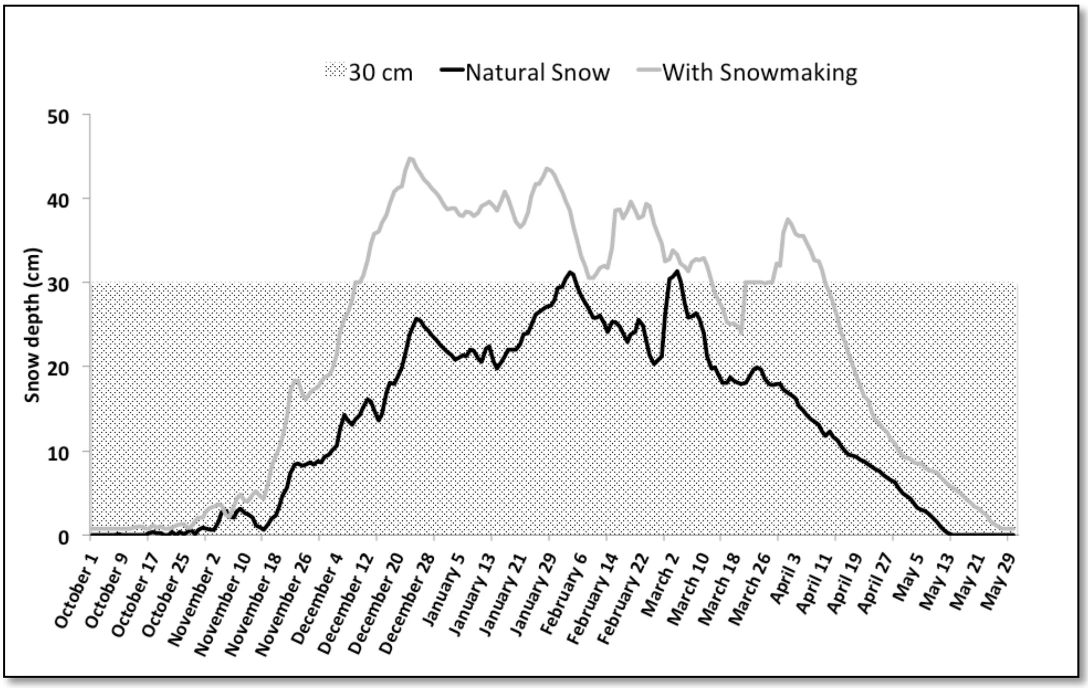


Figure 2.10. Snowpack in Pal assuming a 2°C increase of the winter average temperature enhanced with snowmaking when the 30 cm threshold is not achieved.

2.3 The vulnerability to climate change of the Pyrenean ski resorts

Three different scenarios have been evaluated in order to analyze the vulnerability of the Pyrenean ski resorts to projected changes in future snowpack. The first scenario simulates the present average winter season while the other two simulate future snow depth assuming a +2°C in winter average temperature (equivalent to RCP 6.0 by the end of the century) as a mid climate change scenario and +4°C increase (equivalent to RCP 8.5 by the end of the century) as a high climate change scenario. Finally, in order to assess the technical reliability of each ski resort, the capacity of the snowmaking systems to extend the season length is included in the two climate change scenarios.

2.3.1 Natural reliability

In order to analyze the natural reliability, the 30 cm threshold has been used to estimate the total number of open days per winter season. We assume that this threshold is the lower boundary in order to consider a ski resort as reliable. Thus, for each ski resort, season lengths have been analyzed taking into account the number of days during an average winter season in which this lower boundary is reached. Using the 100-day criterion (Abegg 1996, Abegg et al. 2007, Chaix 2010, Dawson & Scott 2007, 2010, Scott et al. 2003, Scott & McBoyle 2007, Steiger 2010, Witmer 1986), the ski resorts reaching the 30 cm threshold at least 100 days per winter season are considered as reliable with natural snow conditions and non-reliable otherwise. Figure 2.11 shows as green points the ski resorts that offer natural reliability and as red ones those non-reliable, in a present average winter season (a) and in the two future climate change scenarios assuming an increase of 2°C (b) and 4°C (c).

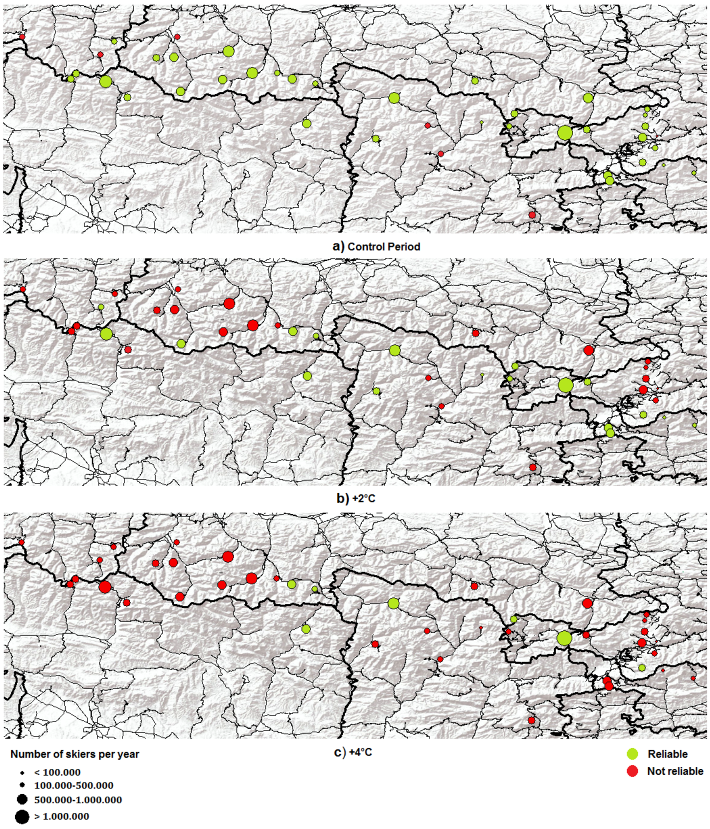
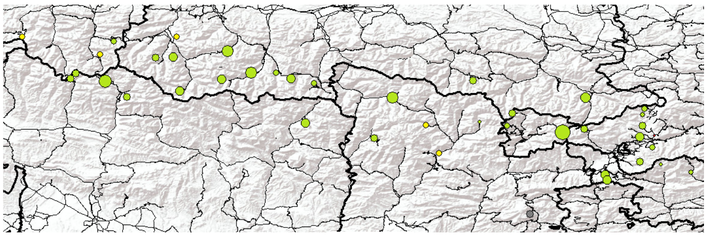


Figure 2.11. Natural reliability of the Pyrenean ski resorts in a present average season (a) and the two future climate change scenarios: +2°C (b) and +4°C (c) of the winter average temperature. The size of the points represents the present average attendance in number of skier attendance during the control period.

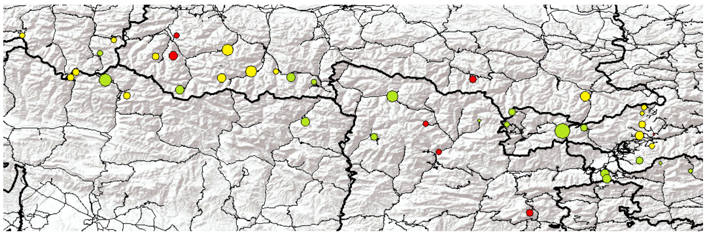
A high variability has been observed on the level of impacts at short distances, not leading to a significant regional pattern about the vulnerability of the Pyrenean ski resorts. In this line, we found that in the same region two resorts located at a really short distance can have significant different level of vulnerability. However, and congruent with previous cited literature, low elevation areas, with a predominance of south oriented slopes present a higher vulnerability. In the particular case of the Pyrenees, those resorts with a higher Mediterranean influence were identified as the more vulnerable to future climate change. Otherwise, those with a higher Atlantic influence, located at higher elevations and more north oriented were identified as the more resilient ones.

2.3.2 Technical reliability

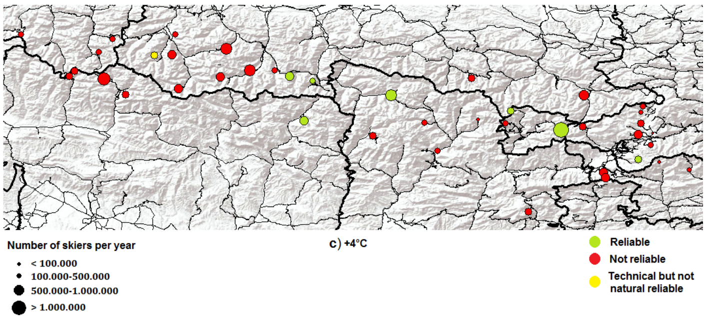
In the last few decades, ski resorts have made considerable investments in snowmaking systems as an efficient way to cope with the natural inter-seasonal variability of snowfall. Since this practice is also considered as one of the main current adaptation strategies to climate change, snowmaking has to be included if we want to achieve a more realistic assessment of climate change impacts. Including the capacity to produce snow in future climate change scenarios will also permit to assess the suitability and the sustainability of this adaptation strategy. In snowmaking, the minimum temperature and the relative humidity are constraining parameters that characterize the capacity to produce snow. In this line, a threshold of -2°C in the minimum temperature has been used in order to model the potential snowmaking days in future climate change scenarios. Climate change will not only affect the available snow pack but also the potential days with the minimum temperature required to efficiently produce snow. Thus, the reliability of each ski resort considering the capacity to produce snow, the technical reliability, has been analyzed and represented in Figure 2.12.



a) Control Period



b) +2°C



c) +4°C

Figure 2.12. Technical reliability of the Pyrenean ski resorts in a present average season (a) and two future climate change scenarios assuming a 2°C (b) and s 4°C increase (c) of the winter average temperature

Figure 2.13 shows the total percentage of the ski resorts in the Pyrenees resulting as naturally and technically reliable in our study. In the present, 83% of the ski resorts are naturally reliable in an average winter season. However, taking into account the capacity of snowmaking, 98% of the ski resorts of the Pyrenees are reliable during a present average winter season. In a future scenario, assuming an increase of 2°C of the winter mean temperature, this share would be reduced to the 44% of the current ski resorts. In a more extreme climate change scenario, that is the scenario assuming an increase of 4°C, the total share of reliable ski resorts in the Pyrenees would be dramatically reduced to only the 7%. When analyzing the snowmaking capacity to offset the natural snow variability, that is the technical reliability, it is observed that these systems can largely enhance and extend the season length in medium climate change scenario, as is the 2°C increase. In this case, the share of technical reliable ski resorts is increased to the 85% of the current ski resorts. However, in a more intense warming scenario (4°C), only a residual effect of the snowmaking systems is observed, where no significant increase of the share of reliable ski resorts is projected.

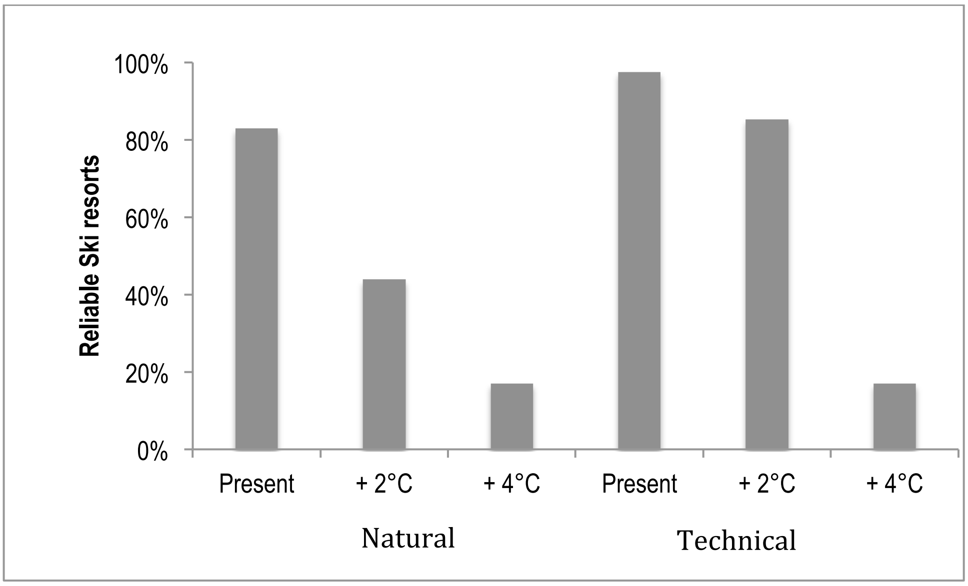


Figure 2.13. Total number of naturally and technically reliable ski resorts in the Pyrenees.

The results achieved in this first approach for the Pyrenean region are in congruence with the majority of studies published to date analyzing the climate change impacts on the ski resorts in different areas around the world such as Northeast USA where reductions on the season length have been projected around the 15% and the 41% (Scott et al, 2008), the 15% and 50% in Ontario (Scott et al, 2008), the 5% and 35% in Quebec (Scott et al, 2007b), or the 14% and 41% in Tyrol, Austria (Steiger, 2010) taking into account a medium-range and high emissions scenario respectively to cite some examples. Even though there is a high geographic variability of the vulnerability to climate change, the reduction of the ski season length is projected both in a medium range (+2°C) and a high climate change scenario (+4°C).

2.4 Main points in review

The main points in review for this chapter are the following:

- The snow model simulations project that snow depth and duration of snowpack in the Pyrenean ski resorts could be strongly affected by future climate change.
- Different climate change scenarios lead to significant differences in the severity of expected changes in snowpack.
- A high geographic variability at very short distances is observed in the vulnerability of the Pyrenean ski resorts.
- Snowpack in the central and eastern areas of the Spanish Pyrenees are clearly the most strongly affected by climate change.
- Low elevated resorts with a higher Mediterranean influence and more south-oriented were identified as the more vulnerable
- Ski resorts with a higher Atlantic influence, located at higher elevations and more north oriented were identified as the more resilient ones.
- In the +2°C scenario snowmaking can significantly enhance the ski season length in many of the Pyrenean ski resorts.
- In the +4°C scenario snowmaking capacity is significantly reduced because the increase of the minimum temperature, a constraining boundary to efficiently produce snow. Therefore, the effect of snowmaking systems is residual in this scenario.

2.5 References

Abegg, B. (1996). *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. vdf Zurich. Zurich

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

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

Beniston, M. (2003). Climatic change in mountain regions: A review of possible impacts. *Climatic Change* 59:5-31

Benoît, R. (1977). On the integral of the surface layer profile-gradient functions. *Journal of Applied Meteorology* 16, 859–860.

Bicknell., S., McManus, P. (2006). The canary in the coalmine: Australian ski resorts and their response to climate change. *Geographical Research* 44:386-400

Botti, L., Goncalves, O., Peypoch, N. (2013) Benchmarking Pyrenean ski resorts. *Journal of Alpine Research,* 100-4.

Breiling, M., Charamza, P. (1999). The impact of global warming on winter tourism and skiing: a regionalized model for Austrian snow conditions. *Regional Environmental Change* 1(1):4-14

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

Chaix, C. (2010). *Climate Change and tourism in the Alps: An analysis based on the pilot sites of the Alpine Space project ClimAlpTour*. Université de Savoie. Institut de la montagne

Christensen, O.B., Christensen, J.H., Machenhauer, B., Botzet, M., (1998). Very high resolution regional climate simulations over Scandinavia present climate. *J Climate* 11:3204-3229.

Christensen, J.H., Carter, T.R., Giorgi, F., 2002. PRUDENCE Employs New Methods to Assess European Climate Change. *EOS*, *AGU*, 83, 147.

Chueca-Cía, J., Julian-Andrés, A.M.A., López-Moreno, J.I., 2003. Variations of Glaciar Coronas, Pyrenees, Spain, during the 20th century. *Journal of Glaciology* 49 (164), 449–455.

Dawson, J., Scott, D. (2007). Climate change vulnerability in the Vermont ski tourism sector. *Annals of Leisure Research* 10(34):550-571

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

Dawson, J., Scott, D. (2010). Systems analysis of climate change vulnerability for the US Northeast ski sector. *Tourism Planning and Development* 7(3):219-235

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. *Climate Res* 20:253-257

Fukushima, T., Kureha, M., Ozaki, N., Fujimori, Y., Harasawa, H (2003). Influences of air temperature change on leisure industries: case study on ski activities. *Mitigation and Strategies for Climate Change* 7:173-189

Galloway, R. (1988) The potential impact of climate change on Australian ski fields. In: Pearman G (ed) *Greenhouse: planning for climatic change*. CSIRO, Melbourne

García-Ruiz, J.M., Puigdefabregas, J., Creus, J., 1986. La acumulación de la nieve en el Pirineo Central y su influencia hidrológica. *Pirineos* 127, 27–72.

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, Australia

Hendrikx, J., Hreinsson, E. Ö, Clark, M.P., Mullan, A.B. (2012). The potential impact of climate change on seasonal snow in New Zealand: part I-an analysis using 12 GCMs. *Theoretical and Applied Climatology*, 110 (4), 607-618

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

Keller, F., Goyette, S., Beniston, M. (2005). Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. *Climatic Change* 72:299-319

König, U., Abegg, B. (1997). Impacts of climate change on tourism in the Swiss Alps. *Journal of Sustainable Tourism* 5(1):46-58

López-Moreno, J.I. (2006). *Cambio ambiental y gestión de embalses en el Pirineo Central Español*. Consejo de Protección de la Naturaleza de Aragón. Zaragoza,
260 pp.

López-Moreno, J.I., 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. Climate Research 36 (3), 203– 217.

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

López-Moreno, J.I., Pomeroy, J., Revuelto, J., Vicente-Serrano, S.M.: (2013). Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. *Hydrological Processes*. 27(18): 2637-2650

López-Moreno, J. I.; Revuelto, J.; Gilaberte, M.; Morán-Tejeda, E.; Pons, M.; Jover, E.; Esteban, P.; García, C.; Pomeroy, J. W. (2013b) The effect of slope aspect on the response of snowpack to climate warming in the Pyrenees. Theoretical and Applied Climatology.

McBoyle, G., Wall, G. (1987). The impact of CO2 induced warming on downhill skiing in the Laurentians. *Cahiers de géographie du Québec* 31(82):39-50

McFarlane, N.A., Boer, G.J., Blanchet, J.P., Lazare, M., 1992. The Canadian climate centre second generation general circulation model and its equilibrium climate. *Journal of Climate* 5, 1013–1044.

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. *Climate Res* 23:171-181

Scott, D., McBoyle, G., Mills, B., Minogue, A. (2006). Climate change and sustainability of ski-based tourismin eastern North America: A reassessment. *Journal of Sustainable Tourism* 14(4):376-398

Scott, D., McBoyle, G. (2007). Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies to Global Change* 12(8):1411-1431

Scott, D., McBoyle, G., Minogue, A. (2007)b. Climate change and Quebec's ski industry. *Global Environmental Change* 17:181–190.

Scott, D., Dawson, J., Jones, B. (2008). Climate change vulnerability of the US Northeast winter recreation Tourism sector. *Mitigation Adaptation Strategies for Global Change* 13:577-596

Scott, D. (2011). Why sustainable tourism must address climate change. *Journal of Sustainable Tourism* Vol. 19, Iss. 1, 2011

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

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

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

Steiger, R. (2012). Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, 20(6), p. 867–882

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

United Nations World Tourism Organization UNWTO (2003) Climate change and tourism. *Proceedings of the First International Conference on Climate Change and Tourism*. Djerba.

Verseghy, D.L., 1991. CLASS – a Canadian land surface scheme for GCMs, I. Soil model. *International Journal of Climatology* 11, 111–133.

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

3. A georeferenced Agent Based Model (ABM) to link the climate-induced changes on snow with the socioeconomic impact on the alpine ski tourism

> *The purpose of models is not to fit the data but to sharpen the questions.*
>
> ***Samuel Karlin***
> **11th R.A. Fisher Memorial Lecture, Royal Society, 20 April 1983**

One of the most challenging issues in climate change is relating the projected physical impacts in ski areas to socioeconomic indicators, such as the shifts in skiers attendance or ski resorts revenues to a snow cover alteration (Dawson et al. 2009). This chapter presents a model coupling the physical impact of climate change such as future snowpack changes with the potential socioeconomic impacts on the winter tourism industry. The model analyzes the potential reduction due to climate change of the season length in the ski resorts of a region, in this particular case Andorra, as well as the subsequent drop in number of skiers and their expenditure. The methodology used is based on a georeferenced Agent Based Model (ABM) that takes into account the skiers response and the adaptive effect of snowmaking on future season length.

3.1 Agent Based Models (ABM) and socioecological systems

ABM, also known in some disciplines as Multi-Agents System (MAS), is defined as a simulation method in which autonomous and heterogeneous agents (i.e., individual people, animals or organizations) share a common environment and interact simultaneously both upon a landscape and among each other led by a self-interest or common interest (Berger & Schreinemachers 2006, Ligmann-Zielinska & Jankowski 2007, Torrens 2003). Spatially referenced ABM appears as a promising approach for exploring complex space-time dynamic interactions between coupled human and environmental systems and capturing emergent macro-level phenomena from micro-level individual actions (Bousquet & LePage 2004, Deadman et al. 2004, Janssen 2009). In recent years, spatially referenced ABM have been used to analyze a broad spectrum of spatial phenomena such as the water and agriculture management (Bithell and Brasington 2009, Feuillette et al. 2003, Smajgl et al. 2009), the dynamics in ancient human and primate societies (Axtell et al. 2002, Janssen 2009), the land use and land cover change (Deadman et al. 2004, Manson & Evans 2007, Parker et al. 2003), the spatio-temporal movement of marine mammals and maritime traffic in the St. Lawrence estuary in Quebec, Canada (Anwar et al. 2007, Parrott et al. 2011), the residential segregation in a city (Crooks 2010) or the spreading of a pine beetle infestation (Perez & Dragicevic 2010). However, because of the novelty of this technique only few studies have applied a georeferenced ABM to model tourism phenomena (Gimblett & Skov-Petersen 2008, Itami et al. 2002, Johnson & Sieber 2009, 2010, 2011).

Georeferenced ABM can also be seen as a type of Planning Support System (PSS). This approach is well suited for scenario development, data analysis, problem diagnosis and policy comparison (Ligmann-Zielinska & Jankowski 2007, Johnson and Sieber 2011). Moreover, the enhancement and the understanding of the interplay between social and ecological systems such as human responses to environmental changes or the impact of their actions upon it can support the decision-making processes by involving cross-disciplinary knowledge (Smajgl et al. 2011).

3.2 Coupling physical changes on snowpack with socioeconomic impacts on the Andorran ski tourism industry

The main goal of this study is to test the capacity of a geo-referenced ABM to couple the physical changes due to climate change to the socioeconomic impacts on a restricted area. Using Andorra as case study, the model analyzes the impacts of climate change to ski industry in terms of ski season length reduction in selected ski resorts and the subsequent drop of skiers and their expenditure. Moreover, the scenarios generated by the model also take into account the effects of snowmaking on enhancing the snowpack and extending the future season length. In this way, more realistic scenarios are generated while the suitability and sustainability of this adaptation strategy can be assessed.

3.2.1 Model description

The model includes regional climate change projections in order to simulate the future snowpack on the different ski resorts of Andorra. A snowmaking module simulates the effect of snow production systems in the enhancement of the natural snowpack. The resulting snowpack at each ski resort will be the dynamic component of the environment upon the agents, in our model the ski visitors, will interact and take their decisions in basis of their internal state and the snowpack state (Figure 3.1).

The model was implemented using the NetLogo software version 5.0 (Wilensky 1999) because it presents a good compromise between a user-friendly ABM programming environment and a powerful GIS extension for the study requirements. The following subsections describe the implementation of the main components of the model, that is, the environment and the agents.

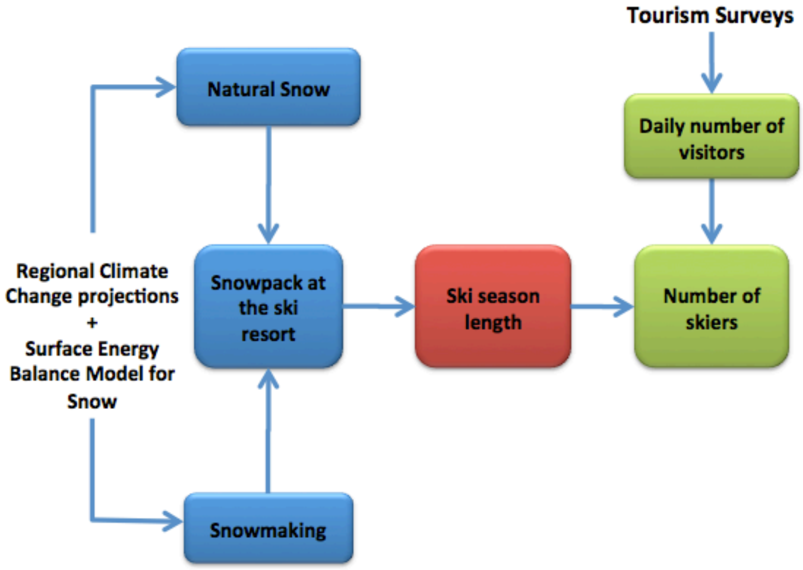
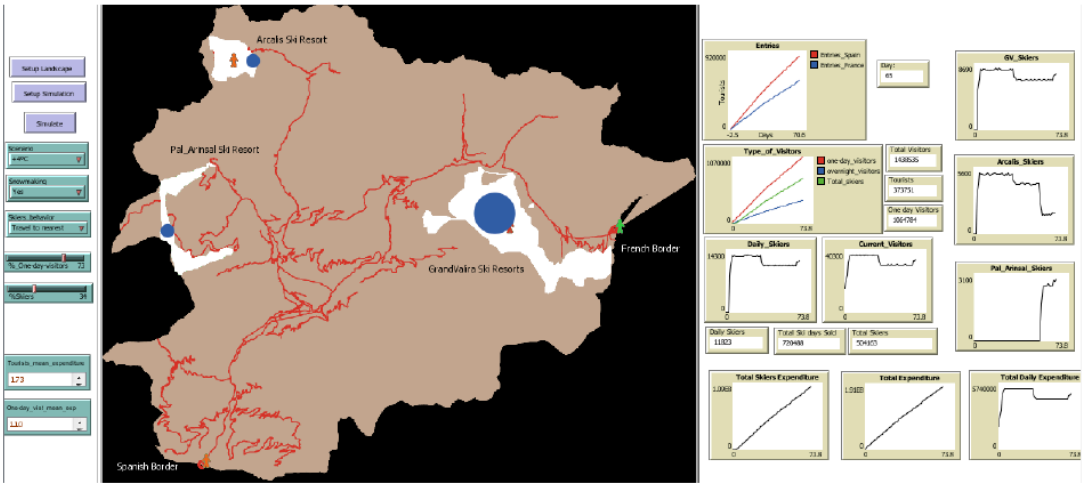


Figure 3.1. Conceptual map of the model

Environment

The environment, that is the space upon the agents interact and respond to its changes, is implemented using four Geographic Information System (GIS) layers: (1) the limits of the country, (2) the entrance points (customs) to Andorra, (3) the main roads connecting the entrance points and (4) the access and the surface area of the three ski resorts: Grandvalira, Arcalís and Pal-Arinsal (Figure 3.2). This latter layer changes over time in basis of the snowpack conditions and determines the season length according to the daily snowpack available in the resort. The first three layers remain static during the simulation.



Scenario
+4ºC

Snowmaking
Yes

Skiers_behavior
Travel to nearest

%_One-day-visitors 73

%Skiers 34

Tourists_mean_expenditure
173

One-day_visit_mean_exp
110

Day:
65

Total Visitors
1438535

Tourists
373751

One day Visitors
1064784

Daily Skiers
11823

Total Ski days Sold
720488

Total Skiers
504163

Figure 3.2. Model interface with the GIS layers used as dynamic environment for the ABM.

Natural Snowpack and Season length

The future natural snowpack at each ski resort is modeled using the methodology presented in the previous chapter to project changes in the daily snowpack of the ski resorts of the Pyrenees. Figure 3.3 shows the mean control period (1960-1990) and future snowpack (assuming a 2°C and 4°C increase of the average winter temperature) at 2000 and 2500 m of elevation for the Andorra case study. The grey area marks the 30 cm threshold showing those days that the snowpack is below the minimum conditions. Once the snowpack reaches this 30 cm value, it is assumed that the ski resort is open.

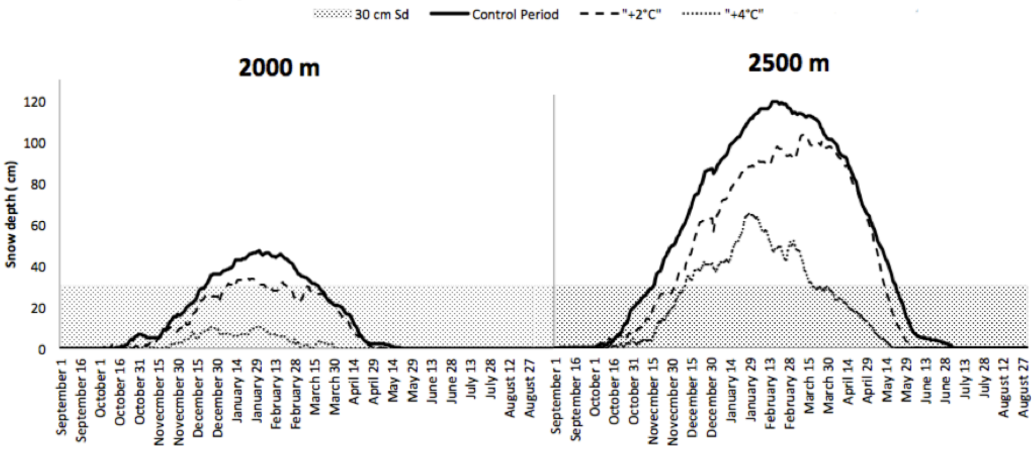


Figure 3.3**.** Mean control period (1960-1990) and future snowpack at 2000 and 2500 m. for the Andorra case study.

The altitudinal distribution of each ski resort was identified in order to assign an altitudinal reference value to simulate the projected snowpack (figure 3.4). This value was approximated to the nearest altitudinal level from those defined in the López-Moreno et al. (2009) study (1500, 2000, 2500 and 3000 m) at which most of the selected ski area is concentrated. We consider this criterion more suited than the usually employed mean elevation (Abegg et al. 2007, Scott et al. 2003, Scott & McBoyle 2007, Steiger 2010) because many ski resorts do not follow a linear altitudinal distribution and usually most of their ski area are concentrated in the highest half of the elevation range. Therefore, because Pal-Arinsal has most of its ski area between 1900 and 2200 m, the 2000 m reference value has been assigned for this resort. In the same way, since most of the Arcalís and Grandvalira skiable area is concentrated between 2250 and 2500, the 2500 m value has been assigned for those ski resorts.

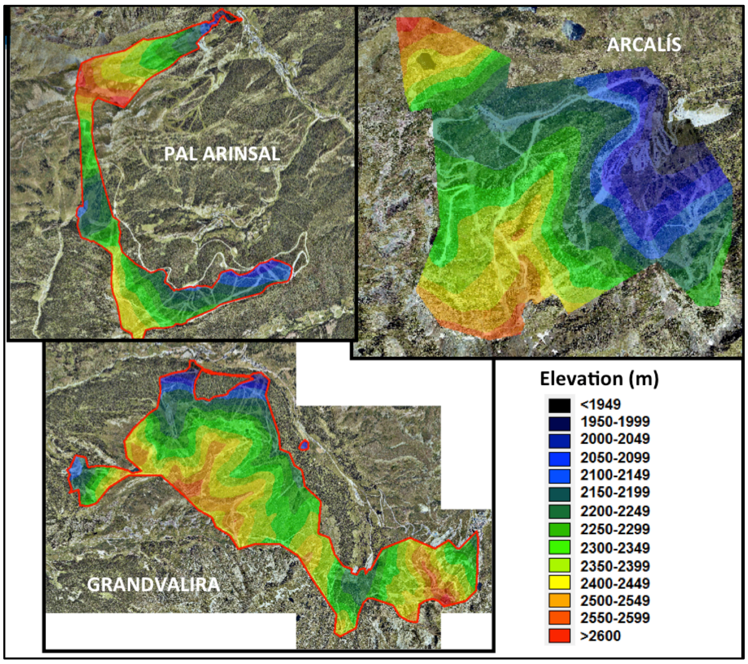


Figure 3.4. Digital Elevation Model of the Andorran Ski resorts

Snowmaking module

With more than 50% of the Andorran ski area now covered by snowmaking production systems, the model includes a snowmaking module simulating the effect of these systems in the enhancement of the snowpack in order to achieve a more realistic projection of the ski season length. In this model, only the snowmaking to assure the minimum snow conditions has been simulated following the same methodology described in the previous chapter. Figure 3.5 shows the enhancement of the natural snowpackat 1900 m following the defined parameters for a +2°C climate change scenario.

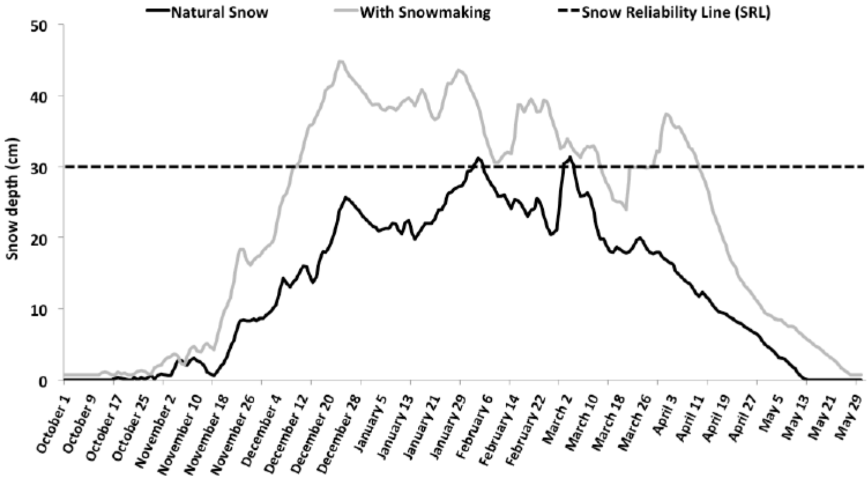


Figure 3.5. Enhancement of the natural snowpack at 1900 m with snowmaking in a +2°C climate change scenario for the Andorran case study.

Entities and attributes

Entities and attributes help to define an ABM (Grimm et al. 2006). An entity is a distinct or separate object or actor that behaves as a unit in the ABM and may interact with other entities or be affected by the environment. The current state of the object is characterized by attributes. An attribute is a variable that distinguishes an entity from other entities of the same type or category, or traces how the entity changes over time. In this model there are two main entities: the skiers, the agents of our model, and the ski resorts, which are fixed on the landscape. Skiers include the following attributes:

- Point of entry to Andorra.
- Visitor type (whether they are one-day visitors or overnight visitors).
- Mean daily expenditure.
- Destination ski resort.
- Current location (coordinates at each time step that locates the agent in the map).

All these attributes except the location are randomly assigned based on the real values and shares of these features obtained from the 2010 national tourism survey (Andorra Turisme, 2010). This survey represents a sample of 4010 international visitors and intends to capture the frequency, nationality, activities and accommodation preferences of Andorra visitors. The location coordinates attribute is updated throughout the simulation according to where the skier is at each time step. Ski resorts have the following attributes:

- Ski season length in days.
- State (whether it is open or closed).
- Location coordinates.
- Reference elevation.

The location coordinates and reference elevation are based on the geographical features of each ski resort. The ski season length and the status of the resorts will change throughout the simulation according to the projected snowpack at the reference elevation of the ski resort described above.

Process overviewing and scheduling

This section defines the actions of each entity, in what order are these actions executed, and when the different state variables are updated. Figure 3.6 shows the main flowchart of the model actions during a simulation. The model starts simulating the snowpack and setting the ski season starting day, ending day and length at each ski resort according to both the selected climate scenario (present, +2°C or +4°C) and if the snowmaking module is activated or not. Once these variables have been computed, the model can set the state of the different ski resorts as open or closed for each day of the simulation. After that, a defined number of agents are created in order to simulate the daily arrival of skiers. The value of the daily number of arrivals will be different each month representing seasonality due to peak and holiday periods such Christmas and Easter. The changes in the daily rate have been set from the monthly statistics of tourist arrivals from the national tourism survey.

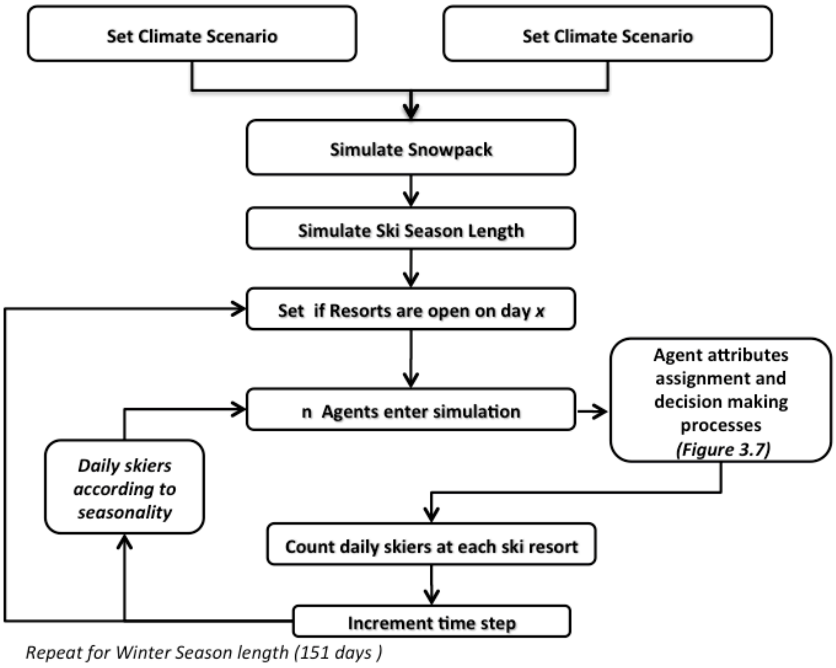


Figure 3.6. Model processes flowchart.

Once these agents (skiers) have been created, they each follow the sequence described in Figure 3.7 to set the attributes value and perform the decision-making response in the model according to agent and landscape attributes. When the agent enters the simulation, it is randomly assigned to a custom of entry and a visitor type based on the real statistical share of the feature. Using values drawn from the tourism survey, the 73% of the agents will be randomly assigned as one-day visitors and the remaining as overnight visitors. If the assigned type is overnight visitor, the attribute length of stay is set to an average value of 3 days and a value of 1 if one-day visitor. In order to compute the daily and total expenditure of the skiers and simulating the difference of the mean expenditure in each type of visitor, the model assigns a value of 173 euros for overnight visitors and 110 euros for one-day visitors. In the same way, based on the attendance statistics, the agent is randomly assigned to one of the different ski resorts. As the type of visitors, all these parameters have been set with the statistical values obtained from the national tourism survey of Andorra (Andorra Turisme 2010).

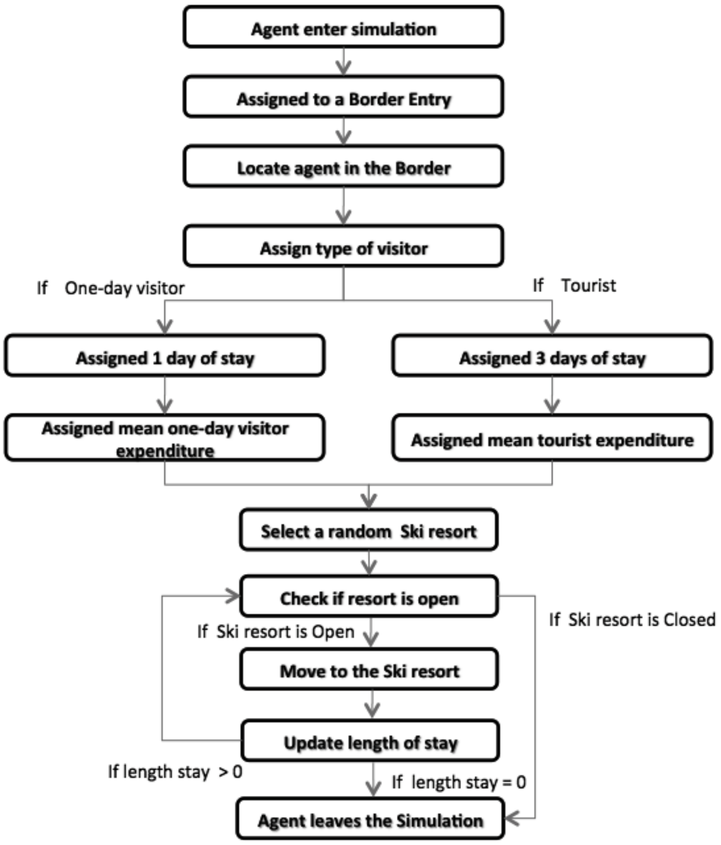


Figure 3.7. Agents decision-making and attribute assignment flowchart.

Once the model has created the daily number of agents and assigned a value to their attributes, the agent checks if the assigned ski resort is open or closed. If it is open, the agent moves to the ski resort. Otherwise, in this first version of the model, the agent leaves the country because there is no opportunity to ski in the selected ski resort. When all the agents have performed the decision making process the model computes the daily number of skiers at each ski resort and their total expenditure during the day. Finally the agents update their length of stay decreasing one day the value of this attribute. The agents with a new value of 0, that is, those that were one-day visitors or in the last day of their stay leave the simulation. In order to simulate a standard winter season, each time step in the model represents 1 day and simulations run for 151 days, from December 1st to April 30th, an entire winter season in Andorra.

3.2.2 Impact on ski season length

Four different scenarios have been run in order to analyze the future impact of climate change-induced snow reductions on the Andorra ski industry. The two first scenarios assume an increase of the mean temperature of +2°C and +4°C respectively. The other two scenarios add the effect of the potential snowmaking on enhancing the natural snowpack and extending the season in the +2°C and +4°C base scenarios. The resulting season length and number of skiers in the three ski resorts of Andorra (Grandvalira, Arcalís and Pal-Arinsal) have been compared with the values of a reference period. The reference season length has been estimated as the average from 2000 to 2010 seasons and the reference attendance of skiers as the average of 2009 and 2010 seasons (Andorra Turisme 2010).

During the reference season, the three ski resorts had an average season length between 139 and 146 days. In the +2°C scenario only the ski resort of Pal-Arinsal, with most of its ski area at a lower elevation, around 2000 m, is affected by a 17% reduction of the season length, mainly at end of the season when snowfall is more erratic (Table 3.1). The other two resorts, with most of their ski area located at higher elevations (above 2200 m), are not affected by this particular climate change scenario (Figure 3.8). Comparing the results with the +2°C with snowmaking scenario it is noticed that the season reduction in Pal-Arinsal would be four times higher without snowmaking. In the +4°C scenario all three ski resorts would suffer serious reductions in their ski season length. The Pal-Arinsal season would be dramatically reduced in half, whereas the Grandvalira and Arcalís would suffer smaller season reductions (8%) at the end of the season. In the same way as +2°C with snowmaking scenario, adding snowmaking to +4°C scenario shows that these systems would help to alleviate these reductions. However, because the worsening of climate conditions will also limit the snowmaking capacity. In this scenario the season length is halved for Pal-Arinsal. Applying the 100-day rule, all three ski resorts would remain reliable in with an increase of +2°C, in the case of Pal-Arinsal, largely thanks to snowmaking. With an increase of +4°C, Pal-Arinsal would not be reliable even with snowmaking, whereas the other two resorts would remain reliable thanks to snowmaking.

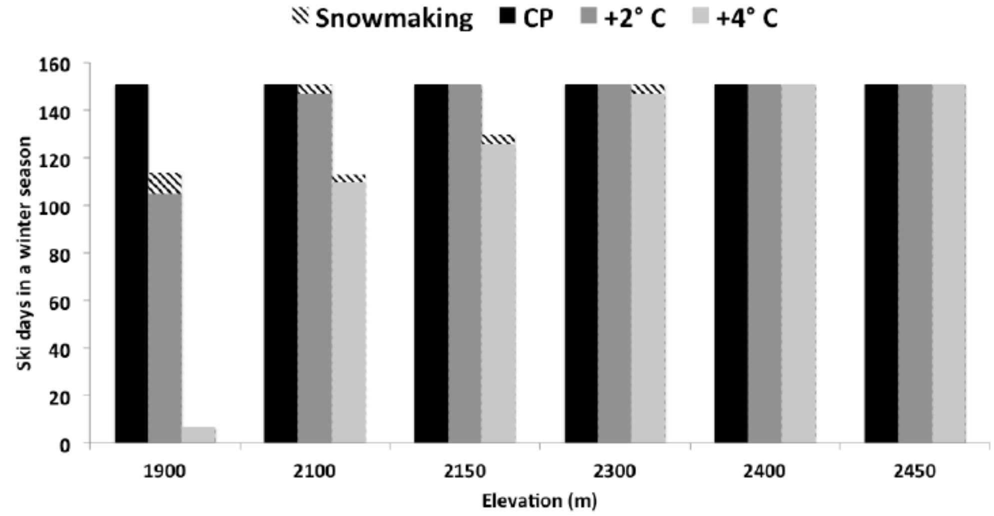


Figure 3.8. Ski days in an average winter season in Andorra with natural snowpack and including snowmaking in the control period and assuming a 2°C and a 4°C increase of the winter average temperature.

		+2° C		+4° C	
Ski Resort	Elevation (m)	Natural Snow cover	With Snowmaking	Natural Snow cover	With Snowmaking
Pal-Arinsal	1900	-30%	-25%	-95%	-95%
	2300	0%	0%	-3%	0%
Arcalis	2100	-3%	0%	-27%	-25%
	2400	0%	0%	0%	0%
GrandValira	2150	0%	0%	-17%	-14%
	2450	0%	0%	0%	0%

Table 3.1. Projected changes in the ski season length at the selected minimum and maximum elevation for each ski resort.

3.2.3 Impact on the number of skiers and their expenditure

The use of an ABM model to simulate the interactions between the environment (snowpack) and the skiers makes it possible to link the season length reductions at each ski resort with the drop of visitors at the regional scale in Andorra, and the related impact on expenditure in the country during a winter season. Table 3.2 shows the drop of the total number of skiers in Andorra under the different scenarios presented in the previous section. In the +2°C scenario, a small drop of the number of skiers and their expenditure is noticed because only the lowest ski resort is affected on the first and last week of the season. On the other hand, the +4°C scenario indicates a more severe drop (-20%) that would lead to a loss of skier-related revenue of approximately 50 M€ (value 2009) per season. In this case, the two ski resorts with higher visitor numbers (Pal-Arinsal and Grandvalira) would be affected both at the beginning and at the end of the season rising the extent of the impacts. Finally, if snowmaking had not been taken into account in the analyses, the impact of the loss of skiers and their expenditure would be much higher, -14% and -50% for the +2°C and +4°C scenarios respectively.

Scenario	No Snowmaking	Snowmaking
+2 °C	-14%	-1%
+4 °C	-50%	-20%

Table 3.2. Projected changes in the total number of skiers.

3.3 Main points in review

The main points in review for this chapter are the following:

- The georeferenced ABM methodology demonstrates potential to simulate the climate change impacts on the winter tourism and particularly to analyze the interaction between physical changes and socioeconomic implications.

- This methodology permits to include the heterogeneity of the skier profile and the behavioral response, very important issues to take into account in this type of studies.

- The reduction on the ski season length and the drop of the number of skiers has been shown to be relevant especially on the lowest elevations in the region of Andorra.

- Snowmaking has a significant impact in Andorra on extending and providing reliable season lengths in low elevation areas with a mid-range climate change scenario and in high elevation areas both with a mid and high-range climate change scenarios.

3.4 References

Abegg B (1996) *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. vdf Zurich, Zurich

Abegg B, Agrawala S, Crick F, de Montfalcon A (2007) *Climate change impacts and adaptation in winter tourism. In: Climate change in the European Alps: adapting winter tourism and natural hazards management*. Paris: Organization for Economic Co-operation and Development

Andorra Turisme (2010) National Survey. Andorra Government

Anwar S, Jeanneret C, Parrott L, Marceau D (2007) Conceptualization and implementation of a multi-agent model to simulate whalewatching tours in the St. Lawrence Estuary in Quebec, Canada. *Environ Modell Softw* 22(12):1775-1787

Axtell RL, Epstein JM, Dean JS, Gumerman GJ, Swedlund AC, Harburger J, Chakravarty S, Hammond R, Parker J, Parker M (2002) Population Growth and Collapse in a Multi-Agent Model of the Kayenta Anasazi in Long House Valley. *PNAS* 99(3):7275-7279

Barnaud C, Bousquet F, Trebuil G (2008) Multi-agent simulations to explore rules for rural credit in a highland farming community of Northern Thailand. *Ecol Econ* 66:615-627

Behringer J, Bürki R, Fuhrer J (2000) Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. *Integrated Assessment* 1(3).331-338

Berger T, Schreinemachers P (2006) Creating agents and landscapes for multiagent systems from random samples. *Ecology and Society* 11(2):19

Bithell M, Brasington J (2009) Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environ Modell Softw* 24 (2):173-190

Bousquet F, Le Page C (2004) Multi-agent simulations and ecosystem management: A review. *Ecol Model* 76(3-4):313-332

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

Chaix C (2010) *Climate Change and tourism in the Alps: An analysis based on the pilot sites of the Alpine Space project ClimAlpTour*. Université de Savoie. Institut de la montagne

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

Crooks AT (2010) Constructing and Implementing an Agent-Based Model of Residential Segregation through Vector GIS. *Int J Geogr Inf Sci* 24(5): 661-675

Dawson J, Scott D (2010) Systems analysis of climate change vulnerability for the US Northeast ski sector. *Tourism Planning and Development* 7(3):219-235

Dawson J, Havitz M, Scott D (2011) Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty. *Journal of Travel and Tourism Marketing,* 28(4):388-404

Deadman PJ, Robinson DT, Moran E, Brondizio E (2004) EFFects of Colonist Household Structure on Land Use Change in the Amazon Rainforest: An Agent Based Simulation Approach. *Environment and Planning B: Planning and Design* 31(5):693-709

Feuillette S, Bousquet F, Le Goulven P (2003) Sinuse: A multi-agent model to negotiate water demand management on a free access water table. *Environ Modell Sof*tw 18(5):413-427

Gimblett R, Skov-Petersen H (2008) *Monitoring, Simulation, and Management of Visitor Landscapes*. University of Arizona, Tuscon.

Grimm V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, Goss-Custard J, Grand T, Heinz SK, Huse G (2006) A standard protocol for describing individual-based and agent-based models. *Ecol Model* 198(1-2):115-126

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

Itami R, Raulings R, MacLaren G, Hirst K, Gimblett R, Zanon D, Chladek P (2002) RBSim 2: Simulating the complex interactions between human movement and the outdoor recreation environment. In *Monitoring and Management of Visitor Flows in Recreational and Protected Areas Conference Proceedings*. Editors: Institute for Landscape Architecture and Landscape Management University of Agricultural Sciences, Vienna, Austria 191-198.

Janssen MA (2009) Understanding artificial Anasazi. *Journal of Artificial Societies and Social Simulation* 12

Johnson PA, Sieber RE (2009) Agent-based modelling: A dynamic scenario planning approach to tourism PSS. In S. Geertman, J., Stillwell (Eds.), *Planning Support Systems: Best Practices and New Methods* (pp. 211-226). Berlin: Springer

Johnson PA, Sieber RE (2010) An Individual-Based Approach to Modeling Tourism Dynamics. *Tourism Analysis* 15(5):517-530

Johnson PA, Sieber RE (2011) An Agent-Based Approach to Providing Tourism Planning Support. *Environment and Planning B: Planning and Design* 38(3):486-504

Kohler TA, Gumerman GJ (1999) *Dynamics in human and primate societies: Agent-based modeling of social and spatial processes*. New York: Oxford University Press.

König U, Abegg B (1997) Impacts of climate change on tourism in the Swiss Alps. *Journal of*

Sustainable Tourism 5(1):46-58

Ligmann-Zielinska A, Jankowski P (2007) Agent-based models as laboratories for spatially explicit planning policies. *Environment and Planning B* 34:316-335

López-Moreno JL, 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

Manson SM, Evans T (2007) Agent-based modeling of deforestation in southern yucatan, mexico, and reforestation in the midwest united states. P*NAS* 104(52): 20678-20683.

Parker DC, Berger T, Manson S, McConnell WJ (2001*) Agent-Based Models of Land-Use and Land-Cover Change*. LUCC Report Series 6(1)

Parker DC, Manson S, Janssen MA, Hoffmann MJ, Deadman P (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. *Ann Assoc Am Geogr* 93(2):314-337

Parrott L, Chion C, Martins CCA, Lamontagne P, Turgeon S, Landry JA, Zhens B, Marceau DJ, Michaud R, Cantin G, Ménard N, Dionne S (2011). A decision support system to assist the sustainable management of navigation activities in the St. Lawrence River Estuary, Canada. *Environ Modell Softwa* 1-16. DOI: 10.1016/j.envsoft.2011.08.009.

Perez L, Dragicevic S (2010) Modeling mountain pine beetle infestation with an agent-based approach at two spatial scales. *Environ Modell Softw* 25(2):223-236

Rixen C, Teich M, Lardelli C, Gallati D, Pohl M, Pütz M, Bebi P (2011) Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential. Mt Res Dev 31(3):229-236

Scott, D, McBoyle, G., Mills, B., Minogue, A (2006) Climate change and sustainability of ski-based tourismin eastern North America: A reassessment. *Journal of Sustainable Tourism* 14(4):376-398

Scott D, McBoyle G (2007) Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies to Global Change* 12(8):1411-1431

Scott D, McBoyle G, Minogue A (2007) The implications of climate change for the Qubec ski industry. *Global Environmental Change* 1:181-190

Scott D, Dawson J, Jones B (2008) Climate change vulnerability of the US Northeast winter recreation Tourism sector. *Mitigation Adaptation Strategies for Global Change* 13:577-596

Smajgl A, Heckbert S, Ward J, Straton A (2009) Simulating impacts of water trading in an institutional perspective. *Environ Modell Softw* 24(2):191-201

Smajgl A, Brown DG, Valbuena D, Huigen MGA (2011) Empirical characterisation agent behaviours in socio-ecological systems. *Environ Modell Softw* 26:837-844

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

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

Torrens PM (2003) Cellular Automata and Multi-agent Systems as Planning Support Tools. In *Planning Support Systems in Practice* Eds S Geertman, J Stillwell (Springer, Berlin) 205-222.

Wilensky U (1999) NetLogo (and NetLogo User Manual), Center for Connected Learning and Computer-Based Modeling, Northwestern University. Available at http://ccl.northwestern.edu/netlogo/

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

4. The climate change impact on the Pyrenees ski tourism: The regional effect of the individual skiers behavioral response to climate change

> *Today we know more about Jupiter than the guy who lives next door to us. We can predict where an election will go, we can turn a gene on or off, and we can even send a robot to Mars, but we are lost if asked to explain or predict the phenomena we might expect to know the most about, the actions of our fellow humans.*
>
> …
>
> *For all practical purposes, our behavior is random. Unpredictable. Episodic. Indeterminable. Unforeseeable. Irregular. There's only one problem with this assumption. It's simply wrong.*
>
> **Albert-László Barabási**
> **Burst: The Hidden Pattern Behind Everything Do**

One main argument for modeling socio-ecological systems is to advance the understanding of dynamic correlations among various human and environmental factors, including impacts and individual responses to environmental change. In this chapter it is explored the shift in skier distribution amongst ski resorts taking into account the behavioral response of individuals due to the impact of climate change on snow conditions. This analysis is performed at a regional scale by means of a coupled gravity and georeferenced agent-based model. This regional approach permitted to assess the potential concurrence among ski resorts with heterogeneous climate vulnerability and tourism attractiveness and the resulting redistribution of skiers based on their behavioral adaptation to climate effects. Therefore, this regional approach allows a more realistic approach than an isolated analysis of the ski resorts.

4.1 A georeferenced ABM coupled to a gravity model to analyze shift in skiers distribution due to individual response to climate change

In recent years ABM models have been identified as a promising methodology to analyze tourism dynamics (Baggio, 2008). First, because they model and characterize interacting human-nature processes of heterogeneous individual behaviors that occur over space and time (Axtell, et al. 2002, 1996; Parker et al. 2003). In an ABM, tourist agents can be characterized with more realistic heterogeneous behaviors, governing activity, decision or accommodation preferences. For example, the visitor response to a ski resort closure, as well as his spatial preferences, such as travel distances. Second, this approach is well suited for scenario development, data analysis, problem diagnosis and policy comparison (Ligmann-Zielinska & Jankowski, 2007; Johnson & Sieber, 2011). Since ABM facilitates the representation of individual-level spatiotemporal interactions, they are relevant to represent and understand the dynamics and characteristics of tourism.

Many studies dealing with tourism are focused on how climate change will affect the supply side of tourism, such as resorts, facilities or season days (Scott et al., 2003, 2008; Becken, 2005; Hoffmann et al., 2009; Steiger, 2010; Pütz et al. 2011). However, even though recent studies point out that behavioral adaptation of tourists due to spatial, temporal and activity substitution could exert a strong influence on the final output of the climate change impact assessments (Behringer et al., 2000; Dawson et al., 2011, Gössling et al, 2012; Dawson et al., 2013), there is no analysis of this issue in the literature. This study proposes a new approach to better understand and explore how the potential behavioral responses identified in previous studies could affect the final outcome of climate change impact assessment. In addition to the identified behaviors and responses of tourists to climate change, this framework could be also applied to explore the influence of tourist behavior and responses to other factors that could affect their dynamics such as energy and transport issues or the influence of crowding in destinations, once this information has been gathered.

The shift in tourist distribution amongst Pyrenean ski resorts is modeled taking into account the behavioral adaptation of individuals due to the impact of climate change on snow conditions. This analysis is performed at a regional scale by means of a coupled gravity and a geo-referenced agent-based model (ABM). Unlike many models used to date, this methodology includes behavioral responses and heterogeneity of winter tourists. The use of a geo-referenced landscape makes it possible to capture the intrinsic spatial features of tourism phenomena, such as ski resort location and travel distances between them. In addition, the ABM model is linked to a gravity model: the potential redistribution of skiers among ski resorts when some of these have to close due to poor snow conditions, depends on the attractiveness of each ski resort and the travel distance between them.

4.1.1 Model description

The "Overview, Design concepts and Details" (ODD) protocol, an accepted standard in ecological and social science literature, is used to formulate and describe the agent-based model (Grimm et al., 2006; 2010). The overview component of this protocol provides an explanation about how the model is designed. Purpose, entities and attributes are then described to define the ABM. The design concepts depict the essential characteristics of the model. Finally the details section describes other information such as input data and submodels needed to understand reimplement and replicate the model.

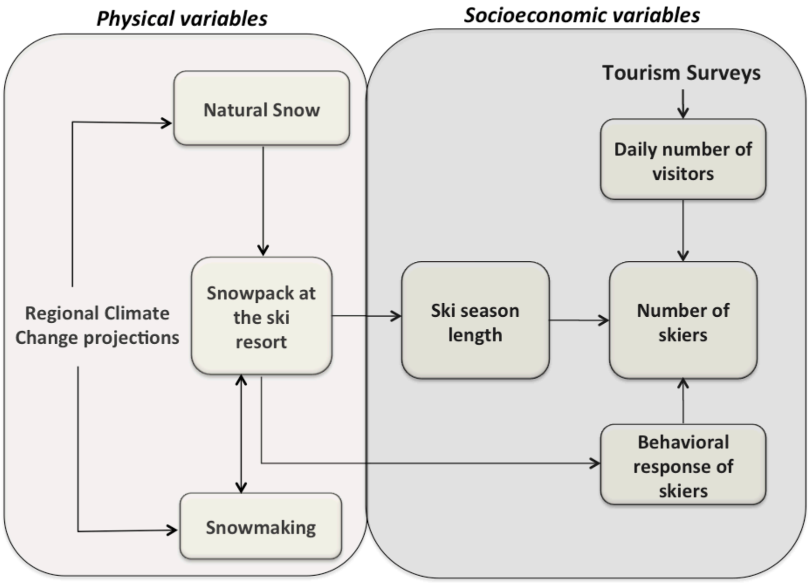


Figure 4.1. Conceptual map of the model linking the physical and the social variables.

Figure 4.1 shows the conceptual map of the model. Climate projections of future snow depth and potential snowmaking capacity at the mean elevation of the resort as well as the daily attendance of skiers at each ski resort are used as input data for the model. Using this information the model simulates by means of a gravity model and an ABM, the future ski season length and the daily attendance of skiers at each ski resort at a regional scale. As case study, the ski industry in the Pyrenean region, including France, Spain and Andorra is analyzed (41 ski resorts).

4.1.1.1 Overview

Purpose

The model is designed to explore questions about the shift in the skier distribution among ski resorts at a regional scale due to future climate change projections affecting local snow conditions at each individual ski resort.

Entities, state variables, scales and environment

In this model there are 2 main entities: skiers, the agents of our model, and ski resorts, which are fixed on the landscape. Skiers include the following attributes:

1) Assigned ski resort.
2) Current location: coordinates at each time step. This internal information helps the software to locate the agent at a ski resort on the map at each time step.
3) Adaptation strategy: whether skiers perform spatial or activity substitution when the ski resort is closed.

Ski resorts include the following attributes:

1) Location coordinates.
2) Season length in days.
3) State: whether the ski resort is open or closed.
4) Maximum capacity of daily skiers.
5) Attractiveness (described in more detail in the submodels section).

The simulation lasts for 151 time steps, the length of a standard winter season (from December 1st to April 30th), being the length of one time step equivalent to one day.

The environment, i.e. the space where the agents interact and respond to its changes, is implemented using two GIS layers: (1) the 41 main ski resorts of the Pyrenees (representing around the 92% of the total skiers (DSF, 2012; Biotti, 2013; ATUDEM, 2013; SkiAndorra) and (2) the main roads connecting the ski resorts (Figure 4.2). The dimension of the points in this layer changes over time based on the daily attendance of skiers (the greater attendance the larger the point is shown) and the status attribute of each ski resort, that is, whether it is open or closed as a consequence of the daily projected snowpack conditions. The first 2 layers remain static during the simulation.

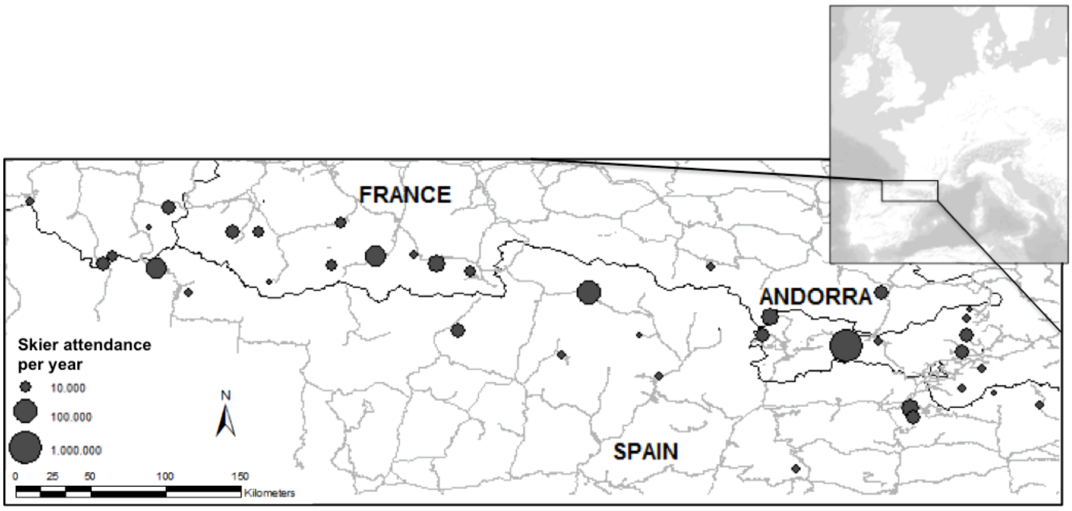


Figure 4.2. GIS layers with the location of the roads and the ski resorts of the Pyrenees. Bullets represent the average skier attendance at each ski resorts (size of the bullet).

Process overview and scheduling

Using the snowpack projections and potential snowmaking days based on future climate scenarios as input data, the model starts simulating the projected season length at each ski resort and updating daily if it is open or closed during an entire winter season (Figure 4.3). The aim of this framework is to allow snowpack and ski days simulations to be used and integrated into the ABM regardless of modeling approach used. In our particular case for the Pyrenees, these variables have been simulated using the projected changes in the Pyrenean daily snowpack during the 21st century by means of a Snow Energy Balance Model (SEBM) for the study area and coupled with technical parameters of ski resorts operation and snowmaking processes, presented in chapter 2.

Therefore, a ski resort is considered open as soon as it reaches the 30 cm threshold considering both natural snow and snowmaking. Snowpack projections are based on 2 future scenarios (+2°C and +4°C) for different altitudinal levels: 1500, 2000, 2500 and 3000 m.

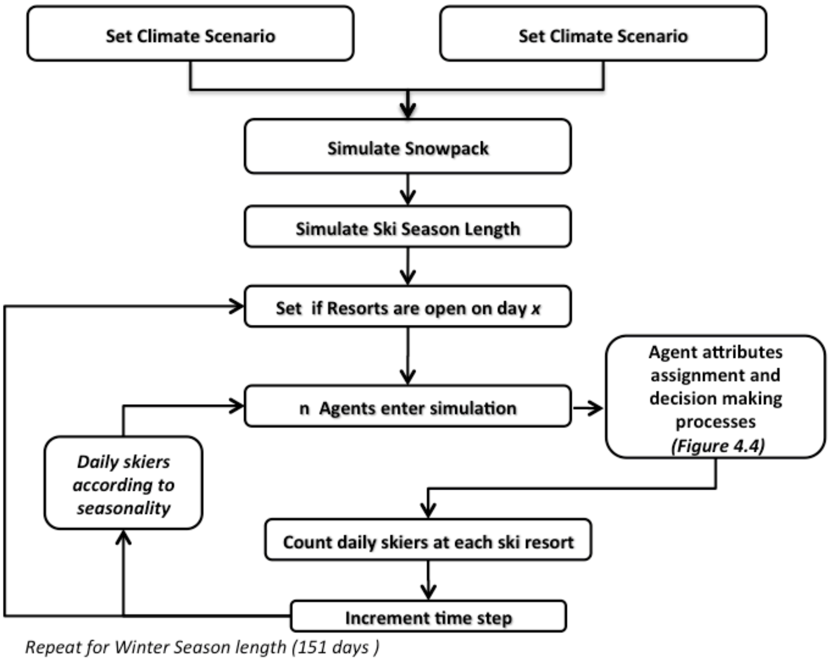


Figure 4.3. Processes involved in the model to simulate a ski season and the skier attendance at each ski resort based on the projected climate and snow scenario.

Based on ski resort statistics and survey data of tourism activity, the model assigns the initial number of agents at each ski resort on the basis of the current distribution of skiers over the studied region. With only aggregated information about skier visits available from official regional ski associations or administrations statistics (DSF, 2012, ATUDEM, 2013, Botti, 2013), and also considering that many ski resorts do not easily or freely share skier numbers, deep research from more than 20 different local and regional newspapers, ski resorts periodical press releases and news websites was conducted to estimate the frequentation at 41 ski resorts of the Pyrenees from 2008-2009 to 2011-2012. From this data, the average from the last 3 seasons was assigned as the average yearly skier visitation at each ski resort. To estimate daily attendance, a daily visitation curve of skiers was estimated in order to modulate the visitation based on holidays, weekends and working days. This issue is a crucial point to the model because the impact of reducing the ski season length is not the same if important holidays such as Easter or Christmas are affected (Steiger, 2013). Information on tourist visits on a daily basis was provided by the national tourism survey from the Andorran Government and statistics from the national tourism department (Andorra Turisme, 2012) for the seasons 2008-2009 to 2011-2012. These surveys were used to develop the profile of the visitors and identify the daily number of skiers. Approximately 8000 visitors to Andorra respond to the national tourism survey every winter season and this information is linked to the observations of the total foreign vehicles entering the country. Table 4.1 shows the data and the sources used as input in the model.

Variable	Source
Snow depth projections	Lopez-Moreno et al. 2009
Coordinates of the ski resorts	GIS layer created by satellite imagery (ICC; SIGMA; Geoportail France; Google Earth)
Ski resorts yearly attendance from 2008-2009 to 2011-2012 seasons	Ski Andorra; Atudem, DSF; Press reports and newspapers
Total length of ski slopes	Ski resorts official webpage
Price of the day ski pass	Ski resorts official webpage
Complementary activities	Ski resorts official webpage
Vicinity to commercial area	GIS layer of cities and villages from France Andorra and Spain (ICC; SIGMA; Geoportail France; Google Earth)
Daily attendance curve of skiers	Andorra Turisme; Estadistica.ad

Table 4.1. Data and sources used in the model.

To explore the emergent macro-level phenomena from micro-level individual actions and local conditions of ski resorts, the model implements the adaptation behavior of skiers through spatial and activity substitution. In one hand, skiers exerting activity substitution in response to changes on snowpack are assumed to stop skiing and shift to a different tourism activity. On the other hand, skiers exerting spatial substitution are assumed to seek for another open ski resort fitting their preferences. Different studies based on surveys (Behringer et al., 2000; Fukushima et al., 2002; Hamilton et al., 2007; Unbehaun et al., 2008; Dawson et al., 2011 and Pütz et al., 2011, Dawson et al, 2013) have identified the potential behavioral and adaptive response of skiers to poor snow conditions. On the basis of these results, the share of potential skiers performing a spatial and an activity substitution are identified and implemented in the model. Thus when a ski resort is closed, the decision-making process shown in Figure 4.4 is applied to each skier at a particular ski resort. These skiers perform an activity substitution and stop skiing when the ski resort where they would typically go skiing is closed. The rest of skiers perform a spatial substitution and are redistributed amongst the remaining open ski resorts in the region by means of a gravity model (described in depth in the submodels section) according to the attractiveness factor of each ski resort and the distance between the origin (in this study, the initially assigned ski resort) and the potential alternative resort.

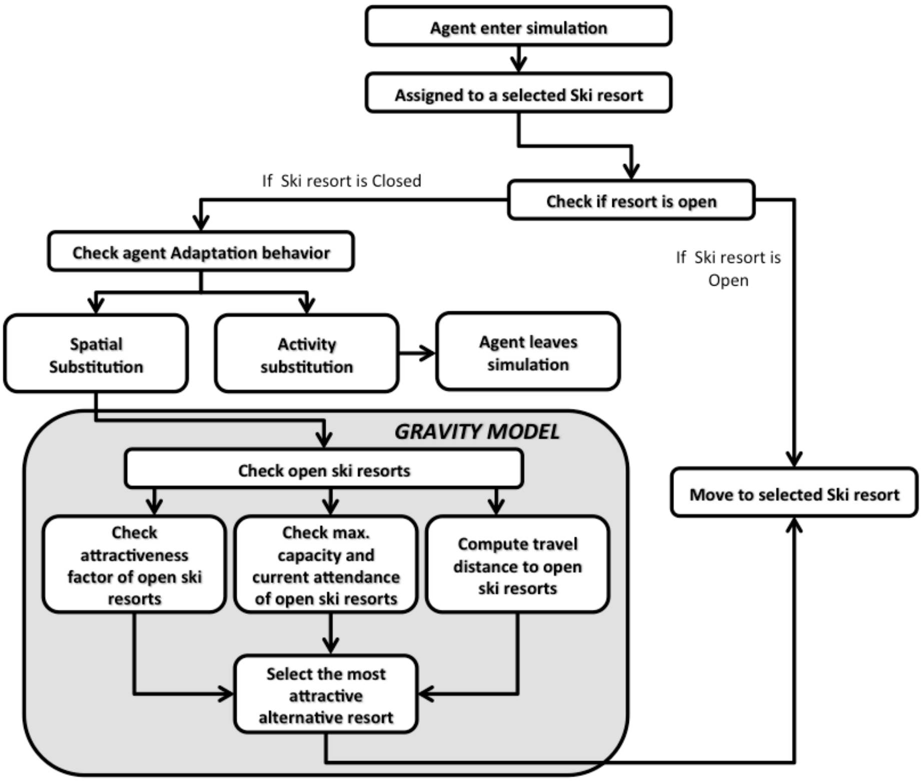


Figure 4.4. Agent decision-making flowchart.

4.1.1.2 Design Concepts

The basic principle addressed by this model is the emergence of potential shifts in the current skiers distribution at a regional scale due to changes in local snow conditions. This concept is addressed by checking how behavioral adaptation of skiers affects the attendance at the local ski resort level, and at the regional scale, by means of the simulation of the potential redistribution of skiers. Skier agents do not implement any learning or prediction capacity and base their decisions solely on the objective of finding a ski resort with suitable snow conditions to support skiing. To achieve this objective, agents are sensitive to four variables: (1) current snow conditions, (2) travel distance between ski resorts, (3) an attractiveness factor of each ski resort and (4) their maximum daily capacity to host skiers. A stochastic process is used to randomly assign the choice of the adaptive behavior (i.e., whether the skiers exert an activity or a spatial substitution). Based on current snow conditions (i.e., the resort is closed due to insufficient snow conditions) agents have a 5% probability to stop skiing. This probability is based on existing surveys (Behringer et al, 2000). Otherwise, skiers exert a spatial substitution and move to an alternative resort characterized by the gravity model. Movement to this alternative resort is restricted by its maximum capacity in order to simulate the influence of crowding. From interviews with ski resort managers, this maximum capacity was assumed as twice the maximum daily attendance during the reference season (average from 2008-2009 to 2011-2012). Although this is a subjective indicator we found it was more realistic than the use of the maximum lift capacity of the resorts. This involves an indirect interaction between agents, affecting the selection of the final destination. In this initial version of the model, no collectives have been implemented. However in further versions collectives could be implemented in order to segregate the adaptation behavior and the preference choices of different profile of skiers such as expert skiers, beginners or families. These differences in preference and adaptation behaviors could also affect the potential redistribution of skiers among ski resorts.

To observe shifts in the distribution of skiers at a regional scale, three different variables are analyzed as model output on a daily basis and for each ski resort: (1) number of attracted skiers when open, (2) number of skiers lost when closed due to insufficient snow depth and (3) total seasonal skier attendance.

4.1.1.3 Initialization

The model is initialized for each future scenario with the projected season length of 151 days, with attendance based on the present regional distribution of skiers. The present average distribution of skiers has been calculated as the average of the historical data of attendance for the winter seasons from 2008-2009 to 2011-2012.

4.1.1.4 Input data

The input data of the model are (1) the current daily distribution of skiers at each ski resort and (2) the days with sufficient snow depth (30 cm indicator), in order to compute the season length during a winter season in different climate scenarios.

4.1.1.5 Submodels

A gravity model, in analogy with Newton's gravity law, is used to analyze the potential redistribution of skiers (spatial substitution) among the ski resorts of the whole region based on both the attractiveness of each ski resort and the travel distance between them when some ski resorts have to close due to poor snow conditions.

Introduced in its contemporary form in 1946 (Zipf, 1946), but with roots that go back to the eighteenth century (Monge, 1781), the gravity law is a spread framework to predict population movement (Monge, 1781; Jung et al. 2008; Thiemann et al. 2010) cargo shipping volume (Isard, 1960; Kaluza et al., 2010), inter-city phone calls (Krings et al., 2009), bilateral trade flows between nations (Pöyhönen, 1963) or migration processes (Kararema et al, 2000), just to name a few. The basic principle governing these models is that the shorter the distance between two objects and bigger their mass, the greater the gravitational pull between these two objects. Following this principle, the gravity law assumes that the number of individuals that move between locations i and j is proportional to the mass, i.e. the population of the source and inversely proportional to the distance to the potential destinations.

The model we describe estimates the total number of skiers moving from a closed ski resort i to an open ski resort j (F_{ij}) on the basis of an attractiveness factor (i.e., mass) of the potential destination resort (G_j) and the inverse of the distance between the origin i and destination resort (D_{ij}), affected by a unique parameter α (Eq. 1).

$$F_{ij} = G_j / D_{ij}^{\alpha} \qquad \text{(Eq.1)}$$

The attractiveness factor represents the capacity of each ski resort to attract skiers to their facilities. To model this feature, a statistical analysis was carried out using a set of 15 physical and socioeconomic variables that characterize the ski resorts. Amongst all variables, four were found to be the most significant in explaining the current redistribution of skiers (table 4.2). A regression model was used to identify the main variables that affect the current capacity to attract skiers and explain the present distribution in the region (Eq. 2). The model used, permits to explain almost 90% of the current distribution of skiers on the Pyrenean region ($R^2 = 0{,}87$; p-value < 0,001) based on four variables: (1) total length of ski slopes, (2) the mean cost of the daily adult ski pass, (3) whether or not the resort offers complementary activities to skiing, and (4) its location, near or distant from a large commercial area. This last qualitative binary variable assigns a value of 1 to those resorts with a commercial area (not only isolated stores) within a radius of 25 km. This indicator permits to identify those resorts with the ability to offer shopping as a complementary activity, a factor identified to have a high influence on tourists when choosing a ski resort (Andorra Turisme, 2012). All these factors are congruent with previous work that identified, through survey research, the most influential factors when choosing a ski destination (Dawson, 2009).

$$\begin{aligned} \textit{Attraciveness Factor} \; &= \beta_1 * \textit{Total Lenght km of slopes} + \beta_2 * \textit{mean daily ski pass} \\ &+ \beta_3 * \textit{Complementary activities} + \beta_4 * \textit{near a commercial center} \end{aligned} \qquad \text{(Eq. 2)}$$

	Spearman's correlation coeff. with total skiers	Sig. (2-tailed)	Coeff. in regression model
Skiable km	0,80	0,000	0,65
Mean daily adult ski pass	0,78	0,000	0,16
Near to a commercial center	0,60	0,016	0,17
Complementary activities	0,55	0,019	0,11

Table.4.1. Most significant variables explaining the current distribution of skiers in Pyrenean resort with the spearman's correlation coefficient, level of significance and the coefficient value in the regression model.

By applying the gravity model when a given resort is closed due to poor snow conditions, we calculate the potential number of skiers that will shift from this closed ski resort to the remaining open resorts. For instance, as Figure 4.5 shows, if the resort of La Molina is closed (in black), the biggest share of its skiers (46%) will shift to the nearest ski resort, Masella, due to the effect of the distance variable. However, due to the different attractiveness of the resorts, a share of the skiers will move to a further resort. Despite being much further away from La Molina, Grandvalira receives a significant share (11%), because of its high attractiveness factor.

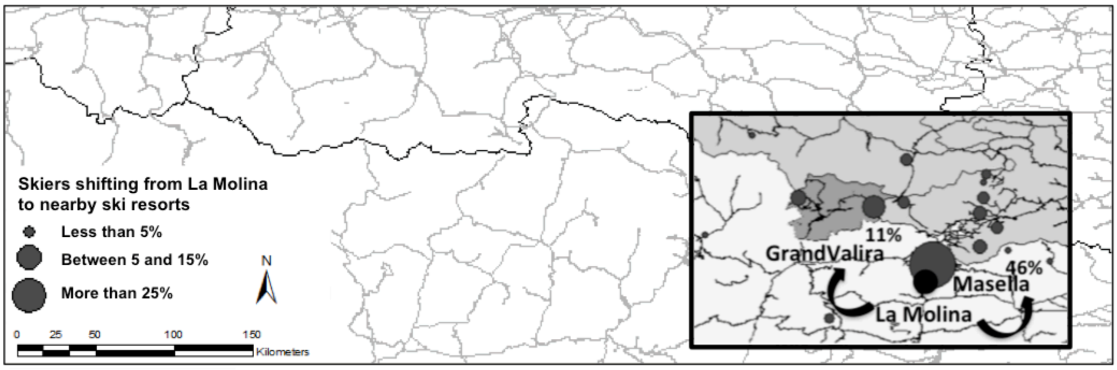


Figure 4.5. Gravity model applied to the skiers of La Molina when it is closed. The size of the grey dots represents the percentage of skiers shifting from La Molina (black dot) to nearby resorts.

4.1.2 Model Validation

One challenge of this modeling approach is the validation process of the model results. Here we use an analogue approach (Dawson et al., 2009) to corroborate our results, since the outcome of the model are simulations of future skiers attendance based on projected ski season reductions. This approach looks for a past winter season with analogous climate conditions that could reproduce a similar situation as the projected future winter season. However, the low frequency in the occurrence of years with analogous conditions to future climate scenarios and the scarcity of detailed historical data on skiers attendance makes it difficult to carry out a good validation process. In this sense, the 2011-2012 season was found to be the one in the last ten years performing the closest climate situation to the +2°C scenario. During this season, the average minimum temperature in Andorra was 2.2°C over the value for the control period (1961-1990), most similar to the +2°C scenario. Thus, the +2°C with snowmaking scenario results are compared to the 2011-2012 skiers attendance, as a form of validation.

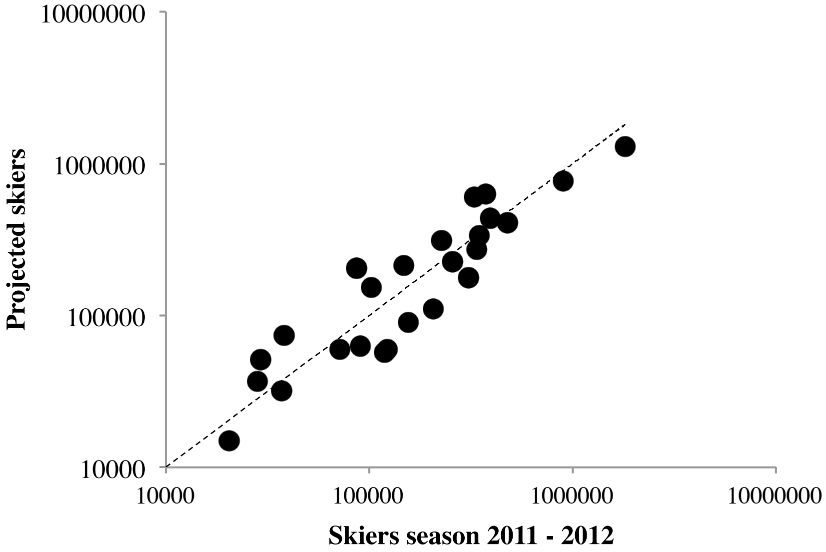


Figure 4.6. Correlation between real skiers for the season 2011-2012 and projected skiers in the +2°C with snowmaking scenario.

Figure 4.6 shows correlated values between projected skiers in the +2°C The model explains remarkably well the real data behavior and no deviation trends are observed. In the resorts where the anomaly of temperature in the analogous year is closer to the projected scenario (central-eastern part of the Pyrenees) the observed error is less than 30%. This error can be explained partly by three main sources:

1) Regional climatic models: there exists a lack of spatial resolution and an inherent uncertainty associated with regional climate models (Alexandru et al., 2007).
2) Quality and quantity of historical data on skiers attendance are not always complete or the desired spatial scale.
3) The model cannot explain temporal substitution (i.e., those skiers not performing spatial substitution, but shifting their skiing season depending on snow availability).

This validation process could be used to assess the usefulness of the gravity approach (Eq. 1). This method relies on adjustable parameters to fit empirical data that vary from region to region (Isard, 1960). In this sense, distance D_{ij} is one of the main variables that can be tuned by means of an exponent a (i.e. D_{ij}^{α}). The best fit result is obtained with $\alpha = 0$ ($R^2 = 0.999$), which implies that, in this particular case study, distance was not a significant influence in explaining the final distribution of skiers. We believe this is due to the very particular characteristics of the ski resorts and the climate of the Pyrenean region, which implies that, in future climate scenarios, skiers are redistributed mainly amongst those resilient (and limited in number) resorts, which are additionally the more attractive ones. Redistribution options for skiers are reduced and so is sensitivity to alpha in D_{ij}^{α}. Furthermore, a limitation in this study is that the distance considered is not the distance from the skier home origin to the potential destination but rather the distance between potential destinations. When the model is run under less severe conditions (i.e., both more homogenous attractiveness and heterogeneous variability in the projected season length reduction), α becomes a significant parameter. Therefore, α should be considered and properly tuned in order to apply this model to other regions.

4.2 Climate change impacts on the skiers attendance in the Pyrenean ski resorts

Four different scenarios were run to analyze the redistribution of future skiers among the Pyrenean ski resorts induced by climate change-related snow reductions. The two first scenarios assume an increase of the winter mean temperature of +2°C and +4°C respectively, taking into account only natural snow conditions. The other two scenarios add the effect of the potential snowmaking on enhancing the natural snow depth and extending the ski season length in the +2°C and +4°C base scenarios. Figure 4.7 shows the attractiveness factor and the projected number of skiers in a present mean winter season and for two future scenarios: assuming an increase of +2°C and +4°C of the winter mean temperature and taking into account only the natural snow depth to compute the ski season length. Two different groups of ski resorts with different attendance patterns can be identified. For most of the ski resorts (≈ 70%), a slight decrease in skier attendance, less than 25%, is projected for a +2°C scenario and a significant decrease, between 50% and 100%, for the +4°C scenario. However, only few resorts are able to increase the number of visitors in both future scenarios due to both a lower climatic vulnerability and a higher touristic attractiveness compared to their competitors. On the other hand, the current relationship between the attractiveness factor of the ski resorts and the total attendance of skiers per year is almost linear (black line in Figure 4.7). In a climate change-induced future, this relationship becomes increasingly non-linear (dashed line in Figure 4.7).

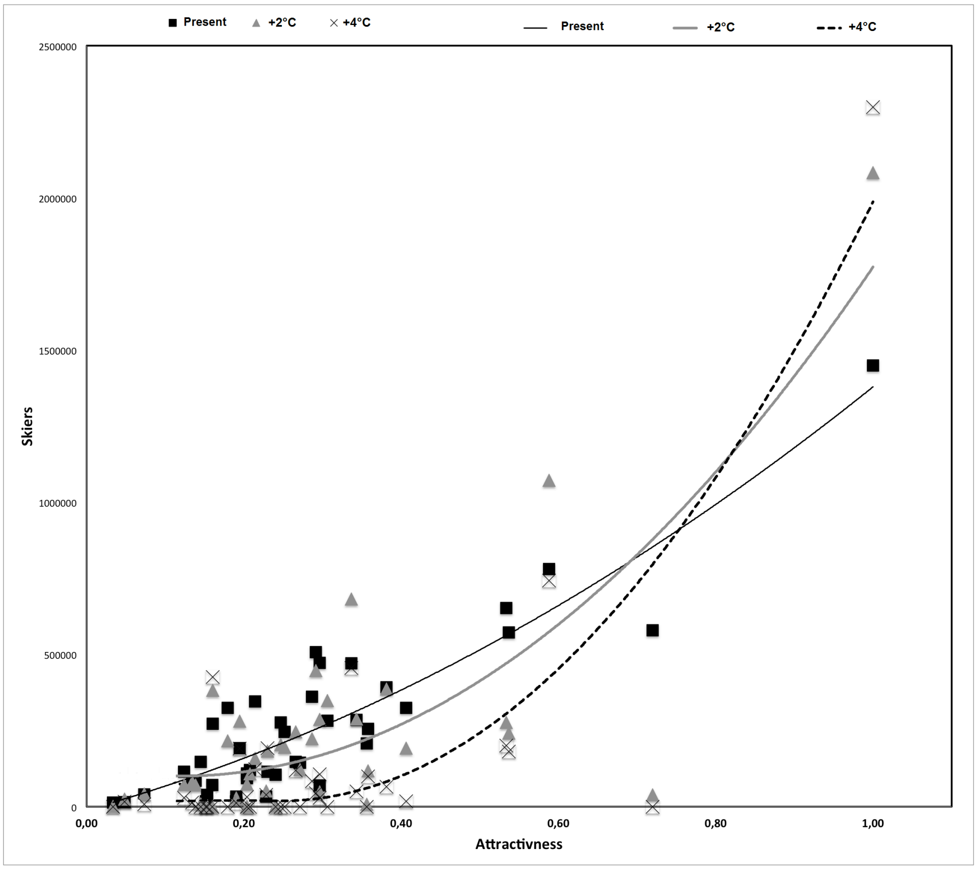


Figure 4.7. Attractiveness factor and changes in total number of skiers for each ski resort in three different scenarios: a mean present winter season and assuming an increase of +2°C and +4°C of the winter mean temperature.

Figure 4.8, shows the attractiveness factor and the projected number of skiers in a present mean winter season and for two future scenarios: assuming an increase of +2°C and +4°C of the winter mean temperature and taking into account the capacity of snowmaking to increase season length.

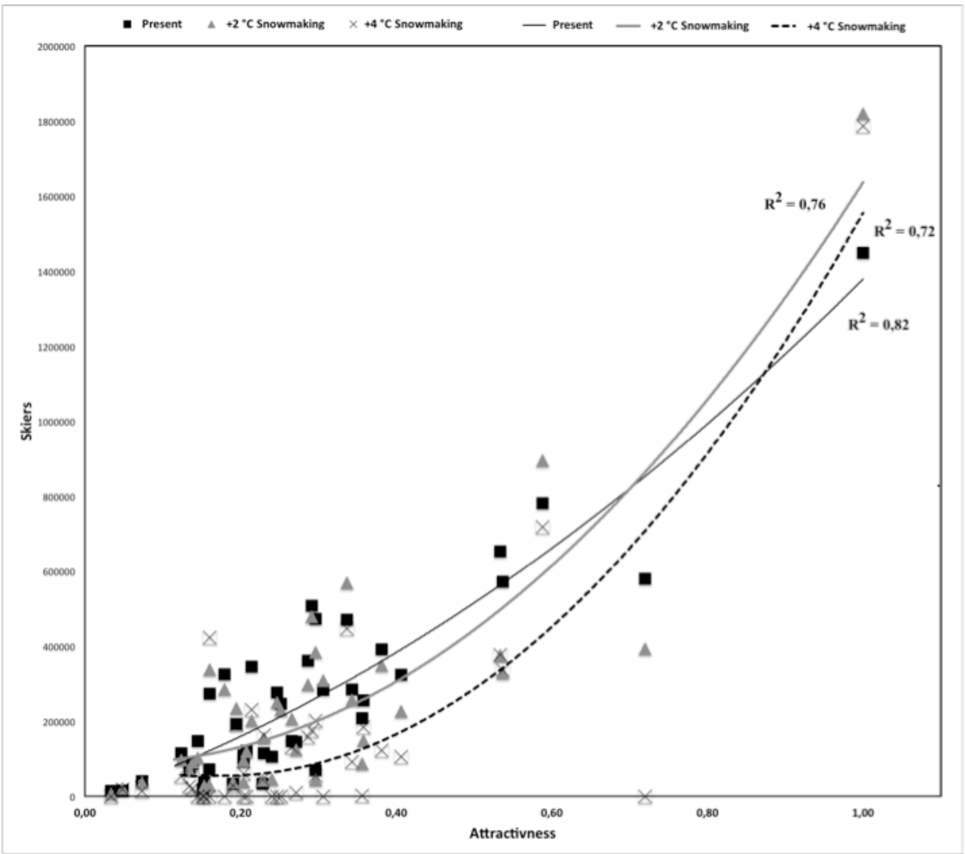


Figure 4.8. Attractiveness factor and changes in the total number of skiers for each ski resort in three different scenarios: a present winter season and assuming an increase of +2°C and +4°C of the winter mean temperature taking into account the contribution of snowmaking.

In this case, three different groups of ski resorts can be identified based on the projected changes to skier attendance and resort attractiveness. The first group of resorts, characterized with a low attractiveness index value, show a slight reduction in future attendance for the +2°C scenario, and in some cases keeps the current attendance of skiers. With this group of resorts, despite taking snowmaking into account, significant decreases in skier visitation are projected for the +4°C scenario. The second group of ski resorts, generally with a medium attractiveness index value, are able to increase their attendance in the +2°C scenario but not in the +4°C, where decreases are projected. Finally, the third group, typically with a higher attractiveness index, shows opposite behavior to the first group, being able to increase future attendance in both scenarios. This demonstrates an outcome of highly attractive ski resorts consolidating their dominant position at the expense of less attractive ski resorts, that may be struggling to adapt to changing snow conditions. Figure 4.9 shows an example of a ski resort classified in this third, 'resilient' group with a high attractiveness index and privileged geographical conditions. This resort has a high capacity to attract the skiers from the more vulnerable resorts located in the surrounding area. However, in snowmaking scenarios, the capacity to attract is reduced. In the +2°C scenario with snowmaking, the vulnerability of surrounding ski resorts is lower and therefore competitiveness is more evenly distributed among resorts. In the +4°C scenario with snowmaking this effect is not as evident due to the reductions of the potential snowmaking days.

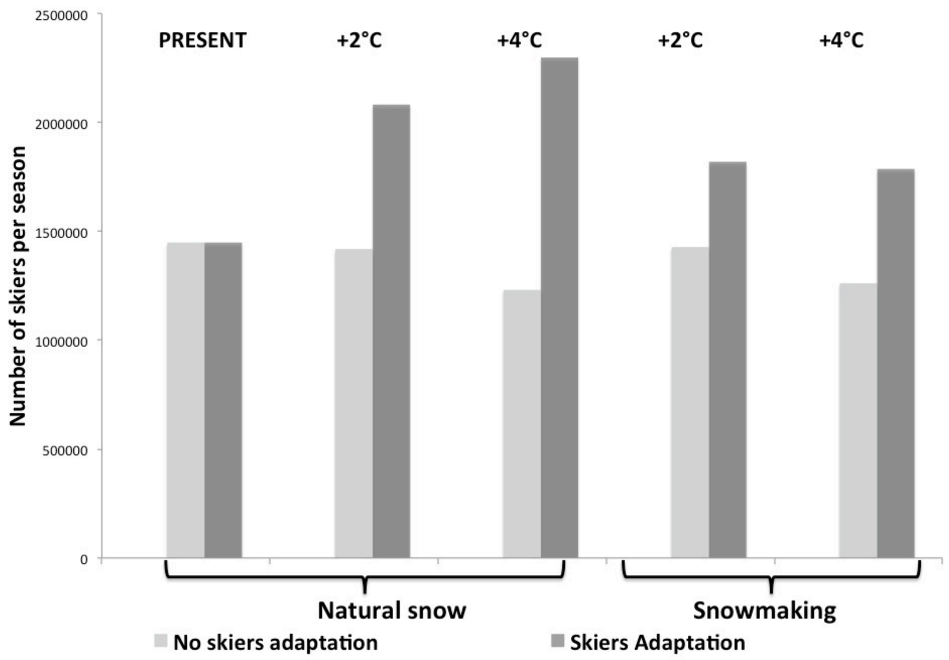


Figure 4.9. Yearly skier attendance in a resilient ski resort in different climate change scenarios with and without behavioral adaptation of skiers.

Regarding the relationship between the attractiveness factor and the total skier attendance in future climate change scenarios, a non-linear pattern is also observed when considering the effects of snowmaking (Figure 4.8). However, although increases in skier attendance are seen with every increase in attractiveness factor, snowmaking leads to a flattening of the curves with respect to the natural snow scenario, mainly in the +2°C scenario. In the case of the +4°C scenario, this effect is less significant since in a high climate change scenario, the effect of the snowmaking to enhance the season length is lower due to fewer potential snowmaking days available in the Pyrenean ski resorts. This change from an almost linear to an exponential relationship between the attractiveness and the total attendance of most of the analyzed ski resorts, results in an increase of the distance between the resilient and the vulnerable ski resort groups.

4.3 Main points in review

The main points in review for this chapter are the following:

- The individual behavioral response of skiers has a significant effect on the assessment of the impact of climate change on the ski industry at a regional scale. In this case for the Pyrenees.
- By means of a gravity model, including the attractiveness of each ski resort, characterized by structural and supply features, and the distances between ski resorts, it is possible to project the potential redistribution of skiers.
- This attractiveness factor is found to affect the vulnerability of each ski resort. Ski resorts able to offer longer ski seasons compared to other ski resorts, plus having a high attractiveness factor are considered to be the most resilient to climate change impacts.
- Due to the low frequency in the occurrence of years with analogous conditions to future climate scenarios and the scarcity of detailed historical data of skier attendance at each ski resort, the validation of the model results is a central challenge to the modeling process.

4.4 References

Abegg, B. 1996. *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. vdf Hochschuleverlag, Zurich.

Alexandru, A., de Elía, R., Laprise, R. 2007. Internal variability in regional climate downscaling at the seasonal time scale. *Mon Weather Rev* 135(9), 3221–3238

Andorra Turisme. 2012. *National Tourism Surveys*. Andorra Government.

ATUDEM. 2013 *Dossier de premsa 2012-2013*. Associación Tursítica de Estaciones De Esquí y Montaña.

Axtell, R. L., Epstein, J. M., Dean, J. S., Gumerman, G. J., Swedlund, A. C., Harburger, J., Chakravarty, S., Hammond, R., Parker, J., Parker, M. 2002. Population Growth and Collapse in a Multi-Agent Model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences* 99(3), 7275-7279.

Baggio, R. 2008. *Symptoms of complexity in a tourism system*. Tourism Analysis 13,1-20

Balbi, S., Giupponi, C., Perez, P., Alberti, M. 2013. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environmental Modelling & Software*, 45,29–51

Bark, R., Colby, B., Dominguez, F. 2010. Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. *Climatic Change* 102, 467–491.

Becken, S. 2005. Harmonising climate change adaptation and mitigation: The case of tourist resorts in Fiji. *Global Environmental Change*, 15 (4), 381-393

Behringer, J., Bürki, R., Fuhrer, J. 2000. Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. *Integrated Assessment* 1(3), 331–338

Bithell, M., Brasington, J., 2009. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environmental Modelling & Software* 24 (2), 173–190.

Botti, L., Goncalves, O., Peypoch, N. 2013. Benchmarking Pyrenean ski resorts. *Journal of Alpine Research*, 100-4.

Crooks, A. T., 2010. Constructing and Implementing an Agent-Based Model of Residential Segregation through Vector GIS. *International Journal of Geographical Information Science,* 24(5), 661-675.

Dawson, J., 2009. Climate Change Vulnerability of the US Northeast Ski Sector: A multi-methods systems-based approach. Thesis (PhD) Department of Geography and Environmental Management, University of Waterloo.

Dawson, J., Scott, D., McBoyle, G. 2009. Climate change analogue analysis of ski tourism in the northeastern USA. *Clim Res* 39,1–9

Dawson, J., Havitz, M., Scott, D., 2011. Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty. *Journal of Travel & Tourism Marketing*, 28 (4), 388-404.

Dawson, J., Scott, D. (2012) Managing for Climate Change in the Alpine Ski Sector. *Tourism Management*. 35, 244-254.

Dawson, J., Scott, D., Havitz, M. 2013. Skier demand and behavioural adaptation to climate change in the US Northeast. *Leisure/ Loisir*, 37(2), 127-143.

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

Fukushima, T., Kureha, M., Ozaki, N., Fujimori, Y., Harasawa, H., 2003. Influences of air temperature change on leisure industries: case study on ski activities. *Mitigation and Strategies for Climate Change 7:173-189*.

Gimblett, R., Skov-Petersen, H., 2008. *Monitoring, Simulation, and Management of Visitor Landscapes*. University of Arizona, Tuscon.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, Grand, T., Heinz, S. K., and Huse, G. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198(1-2), 115-126.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F. 2010. The ODD protocol for describing individual-based and agent-based models: A first update. *Ecological Modelling*, 221, 2760-2768.

Gössling, S., D. Scott, C., Michael Hall, J.-P. Ceron and Dubois, G. 2012. Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, 39(1), 36-58.

Hamilton, L, Brown, C., & Keim, B. D. 2007. Ski areas, weather and climate: Time series models for New England case studies. *International Journal of Climatology*, 27, 2213–2124.

Isard, W. 1960. *Methods of regional analysis: an introduction to regional science*. The MIT Press, Cambridge.

Hoffmann, V H; Sprengel, D C; Ziegler, A; Kolb, M; Abegg, B. 2009. Determinants of corporate adaptation to climate change in winter tourism: an econometric analysis. *Global Environmental Change*, 19(2), 256 -264.

Itami, R., Raulings, R., MacLaren, G., Hirst, K., Gimblett, R., Zanon, D., Chladek, P. 2002. RBSim 2: Simulating the complex interactions between human movement and the outdoor recreation environment. In *Monitoring and Management of Visitor Flows in Recreational and Protected Areas*. Conference Proceedings, A. Arnberger, C. Brandenburg, A. Muhar, Institute for Landscape Architecture and Landscape Management University of Agricultural Sciences, Vienna, Austria, 30 Jan – 02 Feb 2002 pp 191-198.

Janssen, M. A. 2009. Understanding artificial anasazi. *Journal of Artificial Societies and Social Simulation*, 12.

Johnson, P. A., Sieber, R. E. 2009. Agent-based modelling: A dynamic scenario planning approach to tourism PSS. In S. Geertman & J. Stillwell (Eds.), *Planning Support Systems: Best Practices and*

New Methods (pp. 211-226). Berlin: Springer.

Johnson, P. A., Sieber, R. E. 2010. An Individual-Based Approach to Modeling Tourism Dynamics. *Tourism Analysis*, 15(5),517-530.

Johnson, P. A., Sieber, R. E. 2011. An Agent-Based Approach to Providing Tourism Planning Support. *Environment and Planning B - Planning and Design*, 38(3), 486-504.

Jung, W. S., Wang, F., Stanley, H. E. 2008. Gravity model in the Korean highway. *EPL* 81, 48005.

Kaluza, P., Kölzsch, A., Gastner, M. T. & Blasius, B. 2010. The complex network of global cargo ship movements. *J. R. Soc. Interf.* 7, 1093–1103.

Karemera, D., Oguledo, V.I., Davis, B. 2000. A gravity model analysis of international migration to NorthAmerica. *Appl Econ* 32(13), 1745-1755.

Kohler, T. A., Gumerman, G. J. 1999. *Dynamics in human and primate societies: Agent-based modeling of social and spatial processes*. New York: Oxford University Press.

Krings, G., Calabrese, F., Ratti, C., Blondel, V. D. 2009. Urban gravity: a model for intercity telecommunication flows. *J. Stat. Mech*, L07003

Ligmann-Zielinska, A., Jankowski, P. 2007. Agent-based models as laboratories for spatially explicit planning policies. *Environment and Planning B* 34,316-335

López-Moreno, J.L, 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

Manson, S. M., Evans, T. 2007. Agent-based modeling of deforestation in southern yucatán, mexico, and reforestation in the midwest united states. *Proceedings of the National Academy of Sciences*, 104(52), 20678-20683.

Monge, G. 1781. *Mémoire sur la Théorie des Déblais et de Remblais*. Histoire de l'Académie Royale des Sciences de Paris, avec les Mémoires de Mathématique et de Physique pour la même année 666–704 (De l'Imprimerie Royale, 1781).

Parker, D.C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. *Annals of the Association of American Geographers* 93(2), 314-337.

Perez, L., Dragicevic, S. 2010. *Environmental Modelling & Software* 25 (2), 223-236

Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover, È. 2012. Modeling climate change effects on winter ski tourism in Andorra. *Clim Res* 54, 197-207

Pöyhönen, P. 1963. *A tentative model for the volume of trade between countries*. Weltwirtschaftliches Arch. 90, 93–100.

Pütz, M., Gallati, D., Kytzia, S., Elsasser, H. and others 2011. Winter tourism, climate change, and snowmaking in the Swiss Alps: tourists' attitudes and regional economic impacts. *Mt Res Dev* 28, 292–298

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., Dawson, J., Jones, B. 2008. Climate change vulnerability of the US northeast winter recreation– tourism sector. *Mitigation and Adaptation Strategies for Global Change* 13 (5), 577-596.

Simini, F., González, M., Maritan, A., Barabási, A.-L., 2012. A universal model for mobility and migration patterns. *Nature,* 484, 96-100.

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

Smajgl, A., Heckbert, S., Ward, J., Straton, A., 2009. Simulating impacts of water trading in an institutional perspective. *Environmental Modelling & Software* 24(2), 191–201.

Steiger, R. 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Clim Res* 43, 251−262

Steiger R, Abegg B. 2013. The sensitivity of Austrian Ski areas to climate change. *Tourism,planning and development*, 480-493.

Thiemann, C., Theis, F., Grady, D., Brune, R. & Brockmann, D. 2010. The structure of borders in a small world. *PLoS ONE* 5, e15422.

Unbehaun, W., Probstl, U., & Haider, W. 2008. Trends in winter sports tourism: Challenges for the future. *Tourism Review*, 63(1), 36–47.

Viaggi, D., Bartolini, F., Raggi, M. 2009. Combining linear programming and principal–agent models: an example from environmental regulation in agriculture. *Environmental Modelling & Software* 24 (6), 703–710.

Zipf, G. K. 1946. The P1P2/D hypothesis: on the intercity movement of persons. Am. *Sociol. Rev*. 11, 677–686.

5. Conclusion. The vulnerability of the Pyrenean ski resorts and the potential adaptation strategies

> *It's always further than it looks. It's always taller than it looks. And it's always harder than it looks.*
>
> **Mountaineering proverb**

At the beginning of this PhD Thesis several questions were formulated. These were mainly concerned with the vulnerability of the Pyrenean resorts to future shifts on the snowpack due to climate change, the potential socioeconomic implications of these changes on the local and regional economies and the suitability and sustainability of the potential adaptation strategies. Our goal in this work has been to try to answer them by means of an integral assessment, analyzing the physical vulnerability, the social vulnerability and creating a new framework to couple the physical changes on the snowpack of ski resorts with the socioeconomic dimension of the winter tourism industry including the individual behavioral adaptive response of skiers. Even though this research has partially answered these questions, it also has remarked and given some insight about the high uncertainty and limitations when trying to assess future climate change impacts on winter tourism leading to new research questions and new lines to investigate. Even though, the results of this thesis intend to give some insight and raise the awareness among the different stakeholders involved in the winter tourism industry of the Pyrenees.

5.1 The vulnerability from a local perspective

The results achieved in this first approach for the Pyrenean region are in congruence with the majority of studies published to date analyzing the climate change impacts on the ski resorts in different areas around the world. Even though there is a high geographic variability of the vulnerability to climate change, the reduction of the ski season length is projected both in a medium range (+2°C) and a high climate change scenario (+4°C).

On the other hand, the effect of the snowmaking systems to offset the natural variability of the snowpack has been assessed in order to identify the technical reliability of each ski resort. Remarkable results have been found when exploring snowmaking capacity in the two different future climate change scenarios considered in this study. Assuming an increase of 2°C, it is observed that snowmaking can significantly enhance the ski season length in many of the Pyrenean ski resorts. In this scenario the double of the ski resorts are reliable (85%) due to snowmaking systems compared with the natural reliability (44%) representing a softening on the total decrease of skiers in the Pyrenees around the 17%. However, in a more intensive climate change projections, such as the 4°C increase scenario, the snowmaking capacity is significantly reduced. Due to an increase of the minimum temperature, a constraining boundary to efficiently produce snow, the minimum conditions are only reached few days during an average winter season. The effect of snowmaking systems in this scenario is residual, increasing the reliability in only very few ski resorts of the Pyrenees. Thus, snowmaking systems can be considered as a suitable strategy to cope with climate change and inter-seasonal snow variability in the Pyrenees only as long as climate change remains limited to +2°C. Moreover, high economic costs and environmental burdens are associated with this adaptation measure turning the externality assessment a key issue to better characterize the future sustainability of this strategy (Hahn, 2004; Scott & McBoyle, 2007; Steiger & Mayer, 2008; Steiger, 2012; Rixen et al., 2011).

Moreover a high geographic variability is observed in the vulnerability of the Pyrenean ski resorts. These significant changes on the level of impacts at very short distances lead to the observation of no significant regional pattern about the vulnerability. We have found that in the same region there can be two resorts located at a really short distance with significant different level of vulnerability. However and congruent with previous cited literature, low elevation areas, with a predominance of south oriented slopes present a higher vulnerability. In the particular case of the Pyrenees, those resorts with a higher Mediterranean influence were identified as the most vulnerable to future climate change. Otherwise, those with a higher Atlantic influence, located at higher elevations and more north oriented were identified as the more resilient ones. Due to the lack of available data, in this first approach only the future projected snowpack at the mean elevation has been considered to assess the reliability of each ski resort. However, some other physical and geographical local factors such as the altitudinal range distribution, the wind exposure or the surrounding orography play a key role in the availability and spatial distribution of snow in mountain areas. This issue, added to the scarcity of high-resolution regional climate models for the whole area of study, turns the improvement of the accuracy in the snow cover and snowpack projections at each ski resort one of the main challenges for further work.

5.2 The vulnerability from a regional perspective

The last objective of this research was, by means of a georeferenced Agent Based Model (ABM), the exploration of shifts in skier distribution amongst ski resorts at a regional macro-scale, due to changes in local snow conditions as a result of future climate change projections. To date, all studies analyzing the climate change impacts on ski resorts have assessed the potential reductions of skiers separately for each ski resort. This previous approach led in all the projected scenarios to a decrease in skier attendance for all the ski resorts (i.e., Scott et al. 2003, 2008, Dawson et al. 2009, Steiger 2010, Pons-Pons et al. 2012). In contrast with these studies, the approach presented here shows that the vulnerability of the ski resorts within the same geographical region can be affected by the response of skiers to poor snow conditions or closures of the ski resorts. The agent-based model permitted the inclusion of the individual behavioral response of skiers by means of an activity or spatial substitution when their typically frequented ski resort was closed due to poor snow conditions. A new variable, the attractiveness of each ski resort, was included in the analysis of the climate change impacts on the winter tourism. By means of a gravity model, this variable, characterized by structural and supply features of each ski resort, allows, together with distances between ski resorts, to project the potential redistribution of skiers. This attractiveness factor is found to affect the vulnerability of each ski resort. Ski resorts able to offer longer ski seasons compared to other ski resorts, plus having a high attractiveness factor are considered to be the most resilient to climate change impacts.

The second parameter of the gravity model, the travel distance between ski resorts was found not to be significant in the particular case study of the Pyrenees. In this case, the shifting options for skiers, and consequently the sensitivity to alpha factor were highly reduced due to the resulting configuration of vulnerable and resilient ski resorts to climate change. Redistribution options for skiers are reduced and so its sensitivity to alpha in ${D_{ij}}^{\alpha}$. Thus, the effect of distance is hidden because the amount of skiers shifting to these resilient resorts is low regarding the current high frequentation of these ones. Even though distance effect has not a significant impact on the total distribution, it actually has an impact on the reallocation of skiers (skiers moving because ski closures) shifting from one ski resort to another one. Furthermore, a limitation in this study is that the distance considered is not the distance from the skier home origin to the potential destination but rather the distance between potential destinations. When the model is run under less severe conditions (i.e., both more homogenous attractiveness and heterogeneous variability in the projected season length reduction), α becomes a significant parameter. Therefore, α it should be considered and properly tuned in order to apply this model to other regions.

The inclusion of this issue, and complementing the physical vulnerability with socioeconomic factors such as the touristic attractiveness of each ski resort permitted to reach an integral assessment of the local vulnerability at each ski resort and the regional effect on the Pyrenean tourism industry. The result of this analysis allowed the classification of the ski resorts in three different groups of vulnerability (Figure 5.1). A first group consists of highly vulnerable ski resorts that will suffer reduction on its attendance of visitors in both mild and strong climate change scenarios. This group is usually characterized by geographical conditions that make it difficult to ensure a snow-reliable season, such as low elevation (Steiger, 2010; Pons-Pons et al, 2012), south oriented areas, with a predominant Mediterranean influence (Lopez-Moreno et al., 2009) and also a low touristic attractiveness compared to other nearby competitors. A second group consists of low vulnerability ski resorts that will suffer a reduction in attendance under a strong climate change scenario, but not in a mild one, where these resorts would keep their current level of skier attendance or even increase it. This group is usually characterized by ski resorts with medium capacity to assure enough snow and a medium attractiveness factor to capture skiers from other closed ski resorts. Lastly a third group consists of resilient ski resorts, with good conditions to assure future snow availability (high elevations, north oriented slopes, more Atlantic influence and with a high attractiveness factor, which makes them able to offer longer ski seasons than their competitors and to attract skiers from closed ski resorts. Ski resorts classified in this group will increase their skier attendance in both mild and high climate change scenarios. In this context, technical adaptation strategies such as slope management, cloud seeding or snow making could be suitable for the most resilient ski resorts and for low vulnerable in a mid-climate change scenario. However, these adaptation measures could not be enough for the high vulnerable in any future climate change scenario and in a more intense climate change scenario for the low vulnerable resorts. In this case, structural adaptation strategies such as activity and revenue diversification, with more oriented summer activities should be considered and implemented as soon as possible.

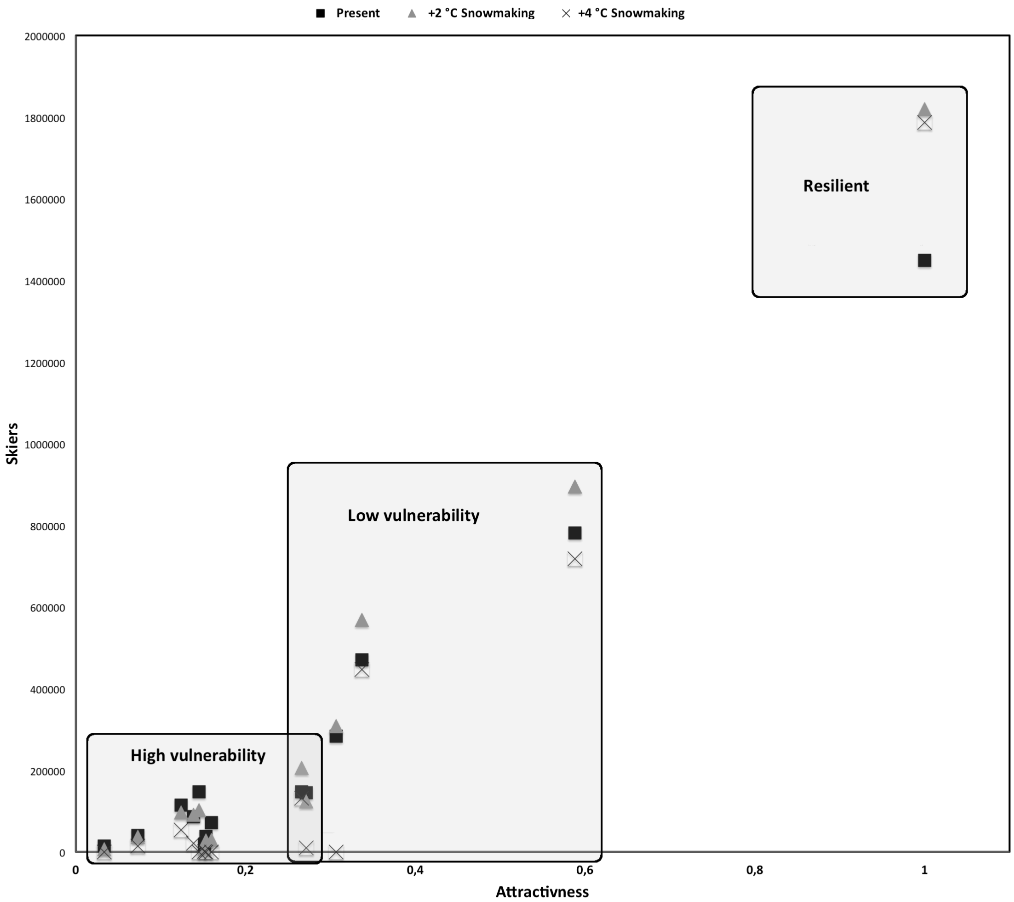


Figure 5.1. Clustering of the ski resorts of the Pyrenees in 3 groups: high vulnerable, low vulnerable and resilient. (In order to present a clearer figure only a few resorts of the Pyrenees are shown in the figure).

Due to the low frequency in the occurrence of years with analogous conditions to future climate scenarios and the scarcity of detailed historical data of skier attendance at each ski resort, the validation of the model results is a central challenge to the modeling process. Despite this constraint, the error of the model is acceptable for a first stage of development. There are several key sources of error that can affect the model outcomes.

- First, there is inherent error of the snow cover and snowpack regional model used and its resolution to capture enough local variability.
- Second, because of high competition between ski resorts, there is limited availability of the skier attendance data, and its reliability should be questioned. This unreliability of resort-sourced data is an issue that could compromise the comparison of projected skiers attendance with the analogous year.
- Finally, since there is no Pyrenean survey so far capturing the adaptive behavior of skiers when confronted with poor snow conditions, results of surveys from different studies in the Alps (Behringer et al., 2000) and USA (Dawson, 2011) were used. In addition to the share of temporal substitution, not taken into account in this study, this issue could also introduce a significant error to the model because the dynamics and the response of the Pyrenean tourists may be different.

5.3 Ongoing and future research

Throughout the research conducted during these years new paths have been discerned. Most of them seek to overcome the main limitations of the methodology and results presented and discussed within these lines while others could complement and give new insight in this field.

- ***Analysis of the externalities of snowmaking in the vulnerability and impact assessment***

Snowmaking systems can be considered as a suitable strategy to cope with climate change and inter-seasonal snow variability in the Pyrenees only as long as climate change remains limited to +2°C. In snowmaking, the minimum temperature and the relative humidity are constraining parameters that characterize the capacity to produce snow. In this line, a threshold of -2°C in the minimum temperature has been used in order to model the potential snowmaking days in future climate change scenarios. Climate change will not only affect the available snow pack but also the minimum temperature required to efficiently produce snow. However other factors besides the meteorological and climatological will affect the future sustainability of the snowmaking as a suitable adaptation strategy. The high economic costs and the environmental burdens associated with these systems turn the externality assessment a key issue to better characterize the future sustainability of this strategy (Hahn, 2004; Scott & McBoyle, 2007; Steiger & Mayer, 2008; Steiger, 2012; Rixen et al., 2011). In this line, the inclusion of the economic, energy and water costs of snowmaking at each ski resort for the different climate change scenarios will permit to improve the vulnerability analysis and achieve a more accurate assessment of the sustainability of this adaptation strategy.

- ***Analysis of the effect of local geographical and meteorological factors on the future snow cover and snowpack projections at each ski resort***

The spatial distribution of snow in mountain areas is characterized for a high variability in very short distances. This variability is the consequence of the complex interaction between mesoscale meteorology and local topography and weather factors. Aspect, slope or the effects of wind-blown (Green and Pickering, 2009) are crucial factors affecting 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). Thus, snowpack dynamics is strongly influenced by aspect (Hinckley, 2012), which affects snow accumulation and melting, especially in areas having a marginal snowpack (McNamara et al., 2005). In this line, it was found that as temperature increased the effect of aspect on accumulation and melting increased, and resulted in greater differences in the maximum snow accumulation and snowpack duration. (López-Moreno et al, 2013). Figure 5.2 shows the average sensitivity per 1°C of the long-term average annual maximum snow water equivalent (MSWE) and duration of the snowpack (DSP) for each slope aspect under different magnitudes of warming. Snowpack thickness and the length of the snow season were found to be highly sensitive to increased temperature, but the magnitude of this effect varied among the analyzed locations. The effect of aspect on snow sensitivity in addition to differences in the elevation and horizon shading were found to be the main causes of this variability. The snowpack on south-facing slopes appears to be particularly vulnerable to climate warming being subjected to greater interannual variability and exhibiting much greater sensitivity as temperature increases (López-Moreno et al., 2013).

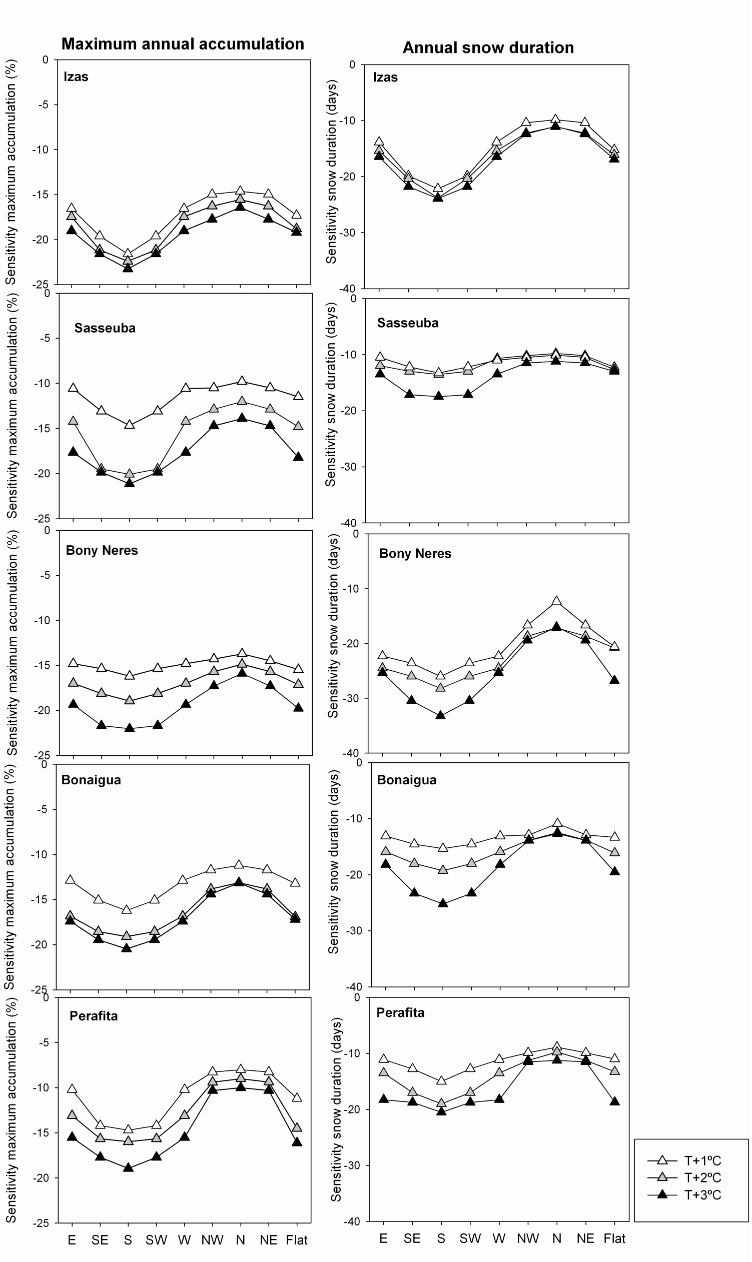


Figure 5.2. Average sensitivity per 1°C of the long-term average annual maximum snow accumulation (MSWE) and duration of the snowpack (DSP) for each slope aspect under different magnitudes of warming (López-Moreno et al., 2013).

Therefore, the inclusion of the effects of local topography when analyzing future snowpack at ski resorts will be key issue to achieve a better vulnerability assessment of the Pyrenean winter tourism industry. This information, could be complemented in a future research with snow cover models with higher spatial resolution, able to better capture the regional variability at a local scale in the future snow depth of each ski resort.

- ***Characterization of the individual adaptation response of skier to future climate change in the Pyrenees***

So far there is no Pyrenean survey capturing the adaptive behavior of skiers when confronted with poor snow conditions or closures. For this reason the present research used results of surveys from different studies in the Alps (Behringer et al., 2000) and USA (Dawson, 2011). Moreover, the surveys available so far, do not capture with accuracy the potential spatial, activity and temporal substitution of skiers or the destination and travel preferences necessary to model with precision the future shifts and redistribution of skiers due to climate change. To overcome this limitation, a common survey will be designed and carried out to capture the behavioral response of visitors when facing poor snow conditions and closures in different ski regions of the world, including Northeast Canada, The Austrian Alps and the Pyrenees. Moreover, the segregation of different adaptive behaviors based on different skier profiles and the influence of the future scarcity of resources like fuel or water, or the influence of crowding in ski resorts will be considered in order to analyze potential sensitive variables that could constraint the ski industry. One of the main limitations of the current model version is the use of the distance. The suitable distance to consider when modeling skiers redistribution should be the distance between the skier home origin and the selected ski resort. Our initial purpose was to build the gravity model using this information. Even though the distance between resorts does not exactly represent the reality of the dynamic with the available data it was the only solution to include in this first version the distance effect on the decision process. To overcome this limitation, the future survey will gather information about the origin and travel behavior of skiers to consider skier home origin and not the frequented ski resort. Finally, the gravity approach, lacking a powerful theoretical guidance, relies on adjustable parameters to fit empirical data that vary from region to region. With this travel information non-parametric approaches like the radiation model (Simini et al., 2012.) could be tested in a future in order to improve the projected redistribution of skiers among the remaining ski resorts.

5.4 Final remark

Aware of the controversial and polemic topic dealt in this research due to the big interests and money in stake, the coverage at local, national and international media exceeded our expectations (Annex II). Some of them showed and alarmist and scaremongering interpretation of the results, some others showed a too optimistic and reductionist one. Some will tell this research calls to alarmism and others that it is too moderate. Even though, the results of this thesis intend to provide a more accurate objective and quantified analysis of the vulnerability of the Pyrenean ski tourism to future climate change. Even though the results, as for any model, cannot be assumed as an accurate prediction but a probable trend, we expect this information can raise the level of awareness of the different stakeholders involved in the winter tourism industry of the Pyrenees, such as regional and local administrations, ski resorts managers and winter tourists as well, and be a starting point to include climate change assessment and sustainability itself as a new design challenge in future strategic planning.

5.5 References

Behringer, J., Bŭrki, R., Fuhrer, J. 2000. Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. Integrated Assessment 1(3), 331–338

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

Dawson, J., Havitz, M., Scott, D., 2011. Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty. Journal of Travel & Tourism Marketing, 28 (4), 388-404.

Dawson, J., Scott, D. (2012) Managing for Climate Change in the Alpine Ski Sector. Tourism Management. 35, 244-254.

Dawson, J., Scott, D., Havitz, M. 2013. Skier demand and behavioural adaptation to climate change in the US Northeast. Leisure/ Loisir, 37(2), 127-143

Green K, Pickering CM (2009). The Decline of Snowpatches in the Snowy Mountains of Australia: Importance of Climate Warming, Variable Snow, and Wind. Arctic, Antarctic and Alpine Research 41 (2): 212-218

Hahn, F. (2004). *L'enneigement artificiel dans l'arc alpin: Rapport de synthèses*. CIPRA Internationale Alpenschutzkommission. Available at www.cipra.org

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

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

López-Moreno, J. I.; Revuelto, J.; Gilaberte, M.; Morán-Tejeda, E.; Pons, M.; Jover, E.; Esteban, P.; García, C.; Pomeroy, J. W. (2013) The effect of slope aspect on the response of snowpack to climate warming in the Pyrenees. Theoretical and Applied Climatology.

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

Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover, È. 2012. Modeling climate change effects on winter ski tourism in Andorra. Clim Res 54, 197-20

Rixen, C., Teich, M., Lardelli, C., Gallati, D., Pohl, M., Pütz, M., Bebi, P. (2011), Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential. *Mt Res Dev* 31(3):229-236

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. *Climate Research*, 23, 171–181

Scott, D., McBoyle, G. (2007). Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies to Global Change* 12(8):1411-1431

Scott, D., McBoyle, G., Minogue, A. (2007). Climate change and Quebec's ski industry. *Global Environmental Change* 17:181–190.

Scott, D., Dawson, J., Jones, B. (2008). Climate change vulnerability of the US Northeast winter recreation Tourism sector. *Mitigation Adaptation Strategies for Global Change* 13:577-596

Simini, F., González, M., Maritan, A., Barabási, A.-L., 2012. A universal model for mobility and migration patterns. Nature, 484, 96-100.

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

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

Steiger, R. (2012). Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, 20(6), p. 867–882

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. International Journal of Climatology 29: 1048-1055

APPENDIX A. ARTICLES

I. López-Moreno, J. I.; Revuelto, J.; Gilaberte, M.; Morán-Tejeda, E.; Pons, M.; Jover, E.; Esteban, P.; García, C.; Pomeroy, J. W. (2014) The effect of slope aspect on the response of snowpack to climate warming in the Pyrenees. *Theoretical and Applied Climatology*, 117:207-219.

II. Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover E. (2012) Modeling climate change effects on winter ski tourism in Andorra. *Clim Res* 54:197-207.

III. Pons, M., Johnson, A. P., Rosas-Casals, M., Jover, E. (2014). A georeferenced agent-based model to analyze the climate change impacts on ski tourism at a regional scale . *Journal of Geographical Information Science*.

IV. Pons, M., López-Moreno, J.I., Esteban, P., Macià, S., Gavaldà, J., García, C., Rosas-Casals, M., Jover, E. (in press). Influencia del cambio climático en el turismo de nieve del Pirineo. Experiencia del proyecto de investigación NIVOPYR de la comunidad de trabajo de los Pirineos (CTP). *Pirineos*, 169. 2014.

ATENCIÓ ¡

Les pàgines 94 a 106 de la tesi contenen l'article I, que es pot consultar a la web de l'editor

ATENCIÓN ¡

Las páginas 94 a 106 de la tesis el contienen el artículo I, que puede consultarse en el web del editor

ATTENTION ¡

Pages 94 to 106 of the thesis are availables at the editor's web

http://link.springer.com/article/10.1007%2Fs00704-013-0991-0

Climate Research, Vol. 54:197-207, 2012

Modeling climate change impacts on winter ski tourism in Andorra

Marc Pons-Pons[1,2,3,*], Peter A. Johnson[3], Martí Rosas-Casals[1,4], Bàrbara Sureda[1], Èric Jover[2]

[1] **Sustainability Measurement and Modeling Lab (SUMMLab), Universitat Politècnica de Catalunya (UPC), EET-Campus Terrassa, 08222 Barcelona, Spain**

[2] **Observatori de Sostenibilitat d'Andorra (OBSA), Placa de la Germandat 7, AD600 Sant Julià de Lòria, Principat d'Andorra**

[3] **Department of Geography, McGill University, 805 Sherbrooke Street West Montreal, Quebec, Canada H3A 2K6**

[4] **ICREA-Complex Systems Lab, Universitat Pompeu Fabra -PRBB, Dr. Aiguader 88, 08003 Barcelona, Spain**

ABSTRACT: Mountain regions have been identified as especially vulnerable areas to climate change. Changes in snowfall, glacier retreat and shifts in biodiversity amount and distribution are some examples of the sensitivity of mountain ecosystems. Moreover, in many mountain economies, reliable snow cover plays a key role as an important resource for the winter tourism industry, the main income source and driving force of local development in such regions. This study presents a georeferenced agent-based model to analyze the climate change impacts on the ski industry in Andorra and the effect of snowmaking as future adaptation strategy. The present study is the first attempt to analyze the ski industry in the Pyrenees region and will contribute to a better understanding of the vulnerability of Andorran ski resorts and the suitability of snowmaking as potential adaptation strategy to climate change. This study projects a reduction on the ski season length and the drop of the number of skiers especially in the lowest elevation ski resort of this region. Moreover, this work indicates that snowmaking cannot completely solve the problem of ensuring snow cover at low elevation ski resorts and should be considered as a suitable short-term strategy, but not as a sustainable long-term adaptation strategy. The resulting model can be used as a planning support tool to help local stakeholders understand the vulnerability and potential impacts of climate change and in the decision-making process of designing and developing appropriate sustainable adaptation strategies to future climate variability.

KEY WORDS: Climate change impacts, Winter tourism, Snowmaking, Adaptation, Agent-based modeling.

*Corresponding author Email address: marc.pons-pons@.upc.edu

1. Introduction

Mountain regions have been identified as especially vulnerable to climate change. The rapid retreat of glaciers, important changes in snowfall amount and frequency and shifts in biodiversity amount and distribution are some examples that demonstrate the sensitivity of mountain ecosystems (Beniston 2003, IPCC 2007). Moreover, in many mountain economies, reliable snow cover plays a key role as an important resource for the winter tourism industry, the main income source and driving force of local development in such regions (Beniston 2003, WTO 2003). The winter tourism industry has been identified by governmental and inter-governmental climate assessments as potentially vulnerable to climate change (CADS 2010, IPCC 2007, WTO 2003). In recent years many studies have analyzed the impacts of climate change on the ski industry in regions such as the European Alps (Abegg et al. 1996, Breiling & Charamza 1999, Chaix 2010, Elsasser & Bürki 2002, König & Abegg 1997, Steiger 2010, Steiger & Mayer 2008, Uhlmann et al. 2009, Töglhofer et al. 2011), Canada (Lamothe & Périard 1988, McBoyle & Wall 1987, Scott et al. 2003, 2006, 2007), USA (Dawson & Scott 2007, 2010, Dawson et al. 2009, Lipski & McBoyle 1991, Scott et al. 2008), Sweden (Moen & Fredman 2007), Australia (Galloway 1988, Hennessy et al. 2003, Bicknell & McManus 2006), Japan (Fukushima et al. 2003), and South Korea (Heo & Lee 2008). All these studies indicate to a greater or lesser extent that climate change will lead to impacts such as ski season length reductions, loss of skiable areas and drop of visitors both in low altitude and low latitude ski resorts.

Andorra is a small and mountainous country located in the middle of the Pyrenees between France and Spain, with a population of nearly 80,000 inhabitants and an area of 468 km2. Andorra receives more than 10 million tourist visits every year (Andorra Turisme 2010). Hence winter tourism is presented as one of the main income sources and driving force of local development. Due to this strong reliance of the Andorran economy on winter tourism, it is critical to evaluate the extent of climate change on the ski industry. A central concern is the possibility that skiing would no longer be viable even with adaptation strategies, such as artificial snowmaking. This has become a critical issue not only to assess the sustainability of the ski industry but the sustainability of the current development model of the entire country. In this context, although the Pyrenean region is presented as one of the most important ski areas in Europe after the Alps, covering the north of Spain, the south of France and Andorra, the vulnerability of this ski industry still remains unexplored (CADS 2010, Scott et al. 2007, Yang & Wan 2010). This paper will analyze the potential reduction of the season length in Andorran ski resorts due to climate change, as well as the subsequent drop in number of skiers and their expenditure. The methodology used is based on a georeferenced Agent Based Model (ABM) that takes into account the skiers response and the adaptive effect of snowmaking on future season length. ABM, also known in some disciplines as Multi-Agents Systems (MAS), is defined as a simulation method in which autonomous and heterogeneous agents (i.e., individual people, animals or organizations) share a common environment and interact simultaneously both upon a landscape and among each other led by a self-interest or common interest (Berger & Schreinemachers 2006, Ligmann-Zielinska & Jankowski 2007, Torrens 2003). Spatially referenced ABM appears as a promising approach for exploring complex space-time dynamic interactions between coupled human and environmental systems and capturing emergent macro-level phenomena from micro-level individual actions (Bousquet & LePage 2004, Deadman et al. 2004, Janssen 2009). In recent years spatially referenced ABM have been used to analyze a broad spectrum of spatial phenomena such as the water and agriculture management (Bithell and Brasington 2009, Feuillette et al. 2003, Smajgl et al. 2009), the dynamics in ancient human and primate societies (Axtell et al. 2002, Janssen 2009), the land use and land cover change (Deadman et al. 2004, Manson & Evans 2007, Parker et al. 2003), the spatio-temporal movement of marine mammals and maritime trafffic in the St. Lawrence estuary in Quebec, Canada (Anwar et al. 2007, Parrott et al. 2011), the residential segregation in a city (Crooks 2010) or the spreading of a pine beetle infestation (Perez & Dragicevic 2010). However, because of the novelty of this technique only few studies have applied a georeferenced ABM to model tourism phenomena (Gimblett & Skov-Petersen 2008, Itami et al. 2002, Johnson & Sieber 2009, 2010, 2011).

Georeferenced ABM can also be seen as a type of Planning Support System (PSS). This approach is well suited for scenario development, data analysis, problem diagnosis and policy comparison (Ligmann-Zielinska & Jankowski 2007, Johnson & Sieber 2011). Moreover, the enhancement and the understanding of the interplay between social and ecological systems such as human responses to environmental changes or the impact of their actions upon it can support the decision-making processes by involving cross-disciplinary knowledge (Smajgl et al. 2011).

The main goal of this study is to analyze, by means of a geo-referenced ABM, the potential climate change impacts on Andorran ski industry in terms of ski season length reduction in selected ski resorts and the subsequent drop of skiers and their expenditure in the region. Moreover, the scenarios generated by the model also take into account the effects of artificial snowmaking on enhancing the snow cover and extending the future season length. In this way more realistic scenarios are generated while the suitability and sustainability of this adaptation strategy can be assessed.

The paper is organized as follows: in section 2, we present the structure and the components of the georeferenced ABM. That is the different layers making up the environment, the agents and their features, and the rules and patterns governing the interactions between agents and the environment. Once the model has been described, section 3 presents the specific scenarios generated in order to assess the future climate impacts on the ski industry and the resulting outcome for each of these different projections. Finally sections 4 and 5 present and discuss the main findings of the paper, the suitability of the methodology used in the study and the further work.

2. Model description

One of the main challenges in climate change impacts studies has been to relate the physical impacts and changes in the environment with their human implications such as socioeconomic impacts or human responses. To overcome this difficulty we present a georeferenced ABM that relates the climate change impacts on the snow cover with their socioeconomic implications in the region. Figure 1 shows the conceptual map with the main components of the model. The model includes regional climate change projections in order to simulate the future snow cover on the different ski resorts of Andorra. A snowmaking module simulates the effect of artificial snow production systems in the enhancement of the natural snow cover. The resulting snow cover at each ski resort will be the dynamic component of the environment upon the agents, in our model the ski visitors, will interact and take their decisions in basis of their internal state and the snow cover state.

The model was implemented using the NetLogo software version 5.0 (Wilensky 1999) because it presents a good compromise between a user-friendly ABM programming environment and a powerful GIS extension for the study requirements. The following subsections describe the implementation of the main components of the model, that is, the environment and the agents.

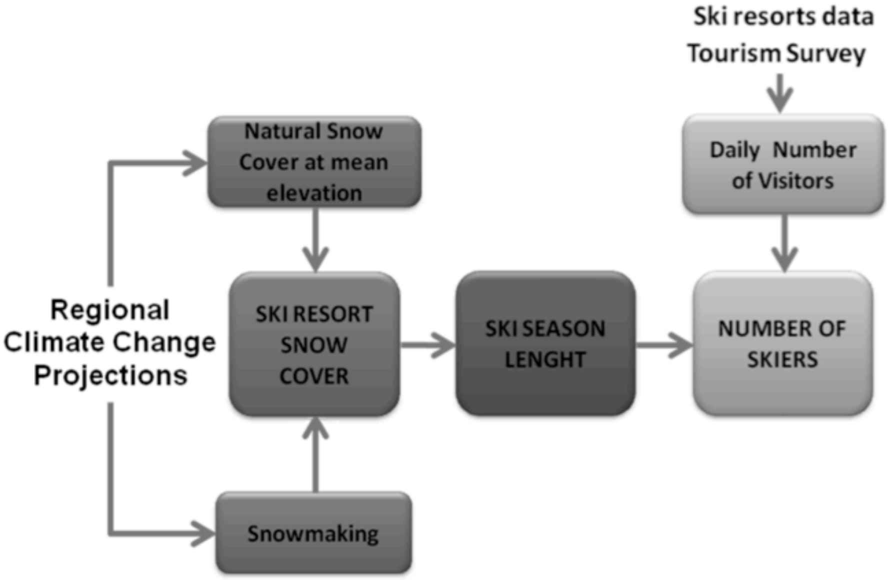


Figure 1: Conceptual map of the model

2.1. Environment

The environment, that is the space upon the agents interact and respond to its changes, is implemented using four Geographic Information System (GIS) layers: (1) the limits of the country, (2) the entrance points (customs) to Andorra, (3) the main roads connecting the entrance points and (4) the access and the surface area of the three ski resorts: GrandValira, Arcalís and Pal-Arinsal (figure 2). This latter layer changes over time in basis of the snow cover conditions and determines the season length according to the daily snowpack available in the resort. The first three layers remain static during the simulation.

Figure 2: GIS layers used as dynamic environment for the ABM

2.1.1. Natural Snow Cover and Season length

The future natural snow cover at each ski resort is modeled using the projected changes in the Pyrenean daily snowpack during the 21st Century from (López-Moreno et al. 2009). This study simulates the snow depth and the snow duration running a Surface Energy Balance Model, the GRENBLS (Keller et al. 2005), with climatic inputs provided by the HIRHAM Regional Climate Model (Christensen et al. 1998). These projections are based on two future emissions scenarios: the SRES A2 and B2 scenarios (IPCC 2007) and for different altitudinal levels: 1500, 2000, 2500, and 3000 m. The ski season length has been simulated using the snowpack projection at a reference elevation of each ski resort and applying a 30 cm threshold. This threshold is one of the most used criterions to assess the climate change vulnerability of ski resorts, the 100-day rule (Abegg 1996, Abegg et al. 2007, Chaix 2010, Dawson & Scott 2007, 2010, Scott et al. 2003, Scott & McBoyle 2007, Steiger 2010, Witmer 1986). This refers to a standard definition for snow reliability assuming that 100 days per season with at least 30 cm of snow depth are required for a ski resort to be economically viable. Applying this criterion, the future season length has been estimated considering those days that the snow cover depth is at least 30 cm. Figure 3 shows the mean control period (1960-1990) and future snow cover (assuming a 2 °C and 4 °C increase of the average temperature) at 2000 and 2500 m of elevation. The grey area marks the 30 cm threshold showing those days that the snow cover is below the minimum conditions. Once the snow cover reaches this 30 cm value, it is assumed that the ski resort is open.

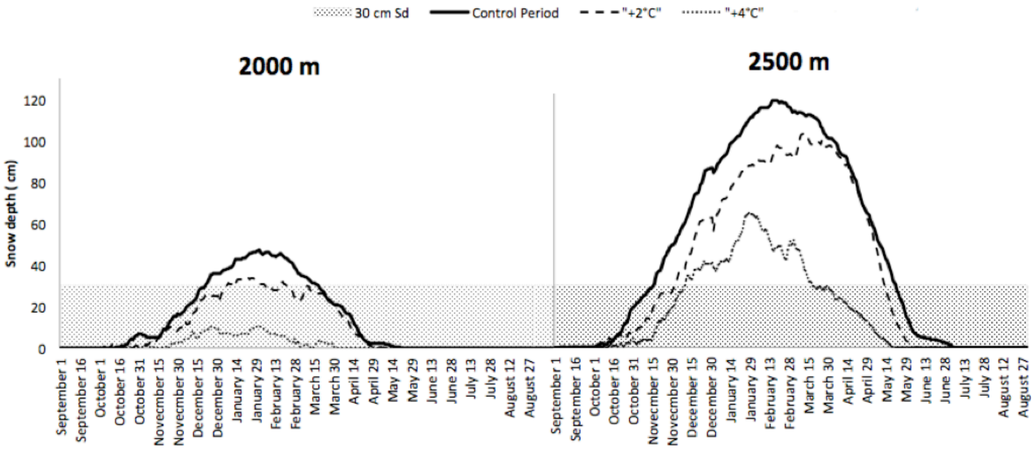


Figure 3: Mean control period (1960-1990) and future snow cover at 2000 and 2500 m.

The altitudinal distribution of each ski resort was identified in order to assign an altitudinal reference value to simulate the projected snow cover (figure 4). This value was approximated to the nearest altitudinal level from those defined in the López-Moreno et al. (2009) study (1500, 2000, 2500 and 3000 m) at which most of the selected ski area is concentrated. We consider this criterion more suited than the usually employed mean elevation (Abegg et al. 2007, Scott et al. 2003, Scott & McBoyle 2007, Steiger 2010) because many ski resorts don't follow a linear altitudinal distribution and usually most of their ski area is concentrated in the highest half of the elevation range. Therefore, because Pal-Arinsal has most of its ski area between 1900 and 2200 m, the 2000 m reference value has been assigned for this resort. In the same way, since most of the Arcalís and GrandValira skiable area is concentrated between 2250 and 2500, the 2500 m value has been assigned for those ski resorts.

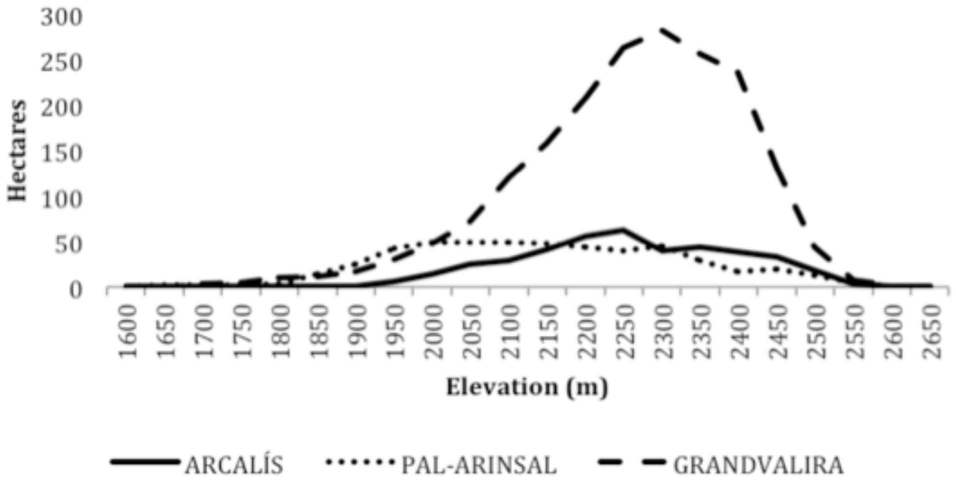


Figure 4: Altitudinal distribution of the andorran ski resorts.

2.1.2. Snowmaking module

Over the last few decades, mainly through high public funding and subsidies, ski resorts across the world have invested significant amounts of money in artificial snow production systems (Steiger & Mayer 2008). This adaptation strategy is intended to offset the variability of snowfall, guaranteeing good ski conditions, scheduled openings, and stable revenues. However, it is important to point out that these investments are not only motivated by climate variability. Snowmaking has also been used as a commercial and image strategy to extend the season and offer better snow conditions with the aim to increase revenues (Steiger & Mayer 2008). With approximately 50% of the Andorran ski area now covered by artificial snow production systems, the model includes a snowmaking module simulating the effect of these systems in the enhancement of the snow cover in order to achieve a more realistic projection of the ski season length. In this model, only the snowmaking to assure the minimum snow conditions has been simulated. The module simulates that a maximum of 10 cm of snow are produced each day as long as the natural snow cover is below the 30 cm threshold (Scott et al. 2003, Steiger 2010). Only those days with a minimum temperature of -5C are considered as potential snowmaking days (Steiger & Mayer 2008). Figure 5 shows the enhancement of the natural snow cover at 2000 m following the defined parameters for a +2° C climate change scenario.

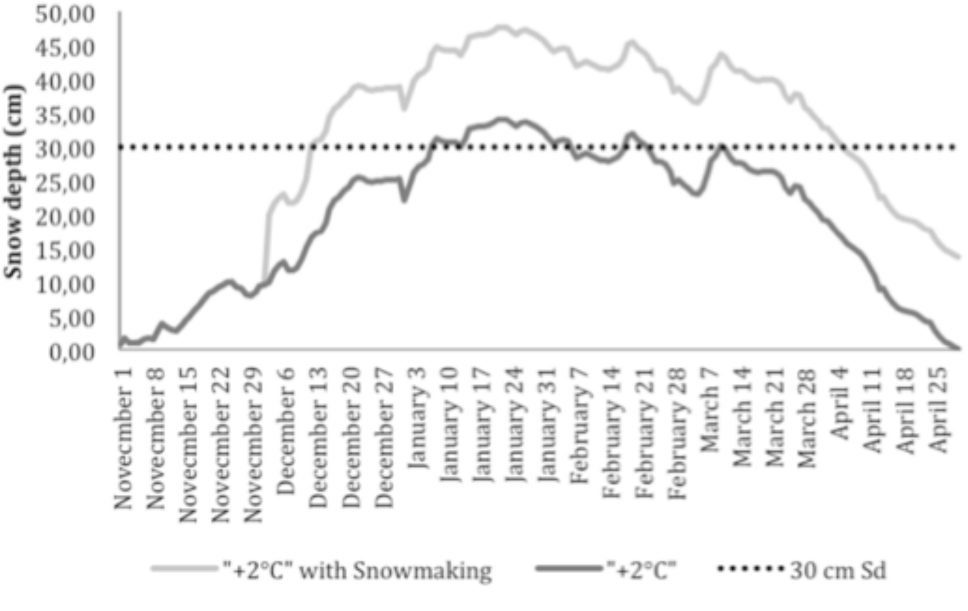


Figure 5: Enhancement of the natural snow cover at 2000 m with snowmaking.

2.2. Entities and attributes

Entities and attributes help to define an ABM (Grimm et al. 2006). An entity is a distinct or separate object or actor that behaves as a unit in the ABM and may interact with other entities or be affected by the environment. The current state of the object is characterized by attributes. An attribute is a variable that distinguishes an entity from other entities of the same type or category, or traces how the entity changes over time. In this model there are two main entities: the skiers, the agents of our model, and the ski resorts, which are fixed on the landscape. Skiers include the following attributes:

- Point of entry to Andorra.
- Visitor type (whether they are one-day visitors or overnight visitors).
- Mean daily expenditure.
- Destination ski resort.
- Current location (coordinates at each time step that locates the agent in the map).

All these attributes except the location are randomly assigned based on the real values and shares of these features obtained from the 2010 national tourism survey (Andorra Turisme, 2010). This survey represents a sample of 4010 international visitors and intends to capture the frequency, nationality, activities and accommodation preferences of Andorra visitors. The location coordinates attribute is updated throughout the simulation according to where the skier is each time step. Ski resorts have the following attributes:

- Ski season length in days.
- State (whether it is open or closed).
- Location coordinates.
- Reference elevation.

The location coordinates and reference elevation are based on the geographical features of each ski resort. The ski season length and the status of the resorts will change throughout the simulation according to the projected snow cover at the reference elevation of the ski resort described above.

2.2.1. Process overviewing and scheduling

This section defines the actions of each entity, in what order are these actions executed, and when the different state variables are updated. Figure 6 shows the main flowchart of the model actions during a simulation. The model starts simulating the snow cover and setting the ski season starting day, ending day and length at each ski resort according to both the selected climate scenario (present, +2 °C or +4 °C) and if the snowmaking module is activated or not. Once these variables have been computed, the model can set the state of the different ski resorts as open or closed for each day of the simulation. After that, a defined number of agents are created in order to simulate the daily arrival of skiers. The value of the daily number of arrivals will be different each month representing seasonality due to peak and holiday periods such Christmas and Easter. The changes in the daily rate have been set from the monthly statistics of tourist arrivals from the national tourism survey.

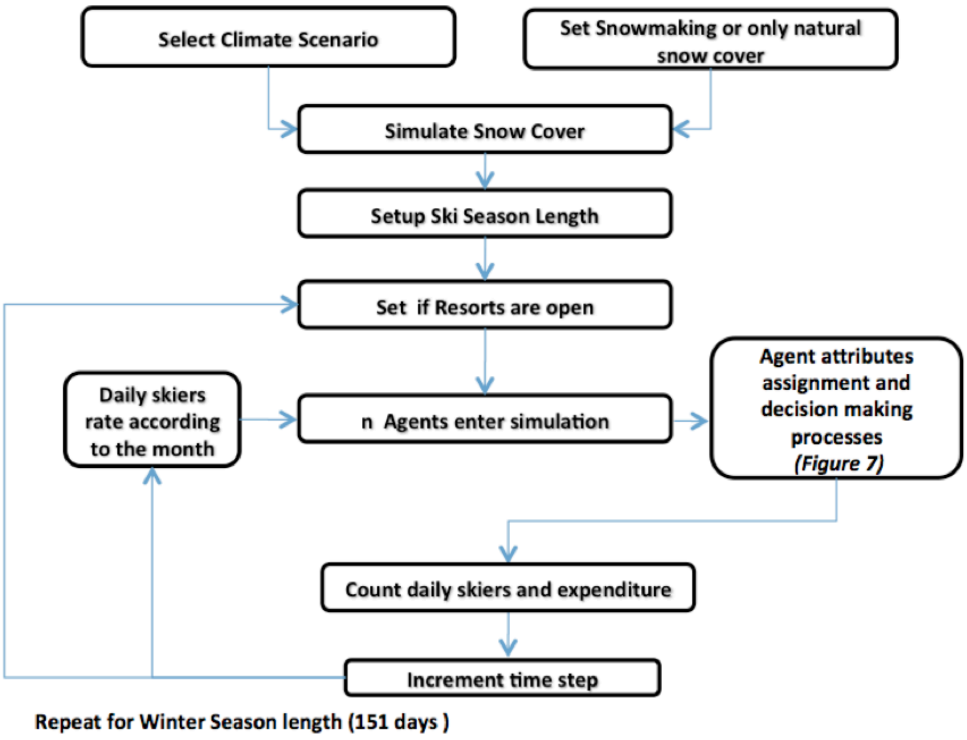


Figure 6: Model processes flowchart.

Once these agents (skiers) have been created, they each follow the sequence described in figure 7 to set the attributes value and perform the decision-making response in the model according to agent and landscape attributes. When the agent enters the simulation, it is randomly assigned to a custom of entry and a visitor type based on the real statistical share of the feature. Using values drawn from the tourism survey, the 73 % of the agents will be randomly assigned as one-day visitors and the remaining as overnight visitors. If the assigned type is overnight visitor, the attribute length of stay is set to an average value of 3 days and a value of 1 if one-day visitor. In order to compute the daily and total expenditure of the skiers and simulating the difference of the mean expenditure in each type of visitor, the model assigns a value of 173 euros for overnight visitors and 110 euros for one-day visitors. In the same way, based on the attendance statistics, the agent is randomly assigned to one of the different ski resorts. As the type of visitors, all these parameters have been set with the statistical values obtained from the national tourism survey of Andorra (Andorra Turisme 2010).

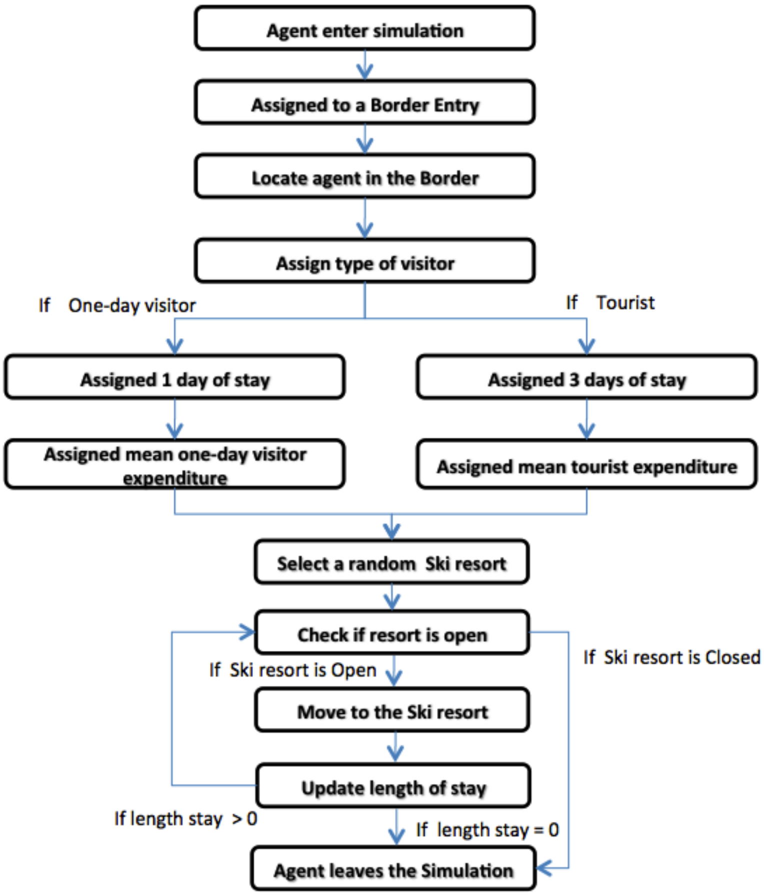


Figure 7: Agents decision-making and attribute assignment flowchart.

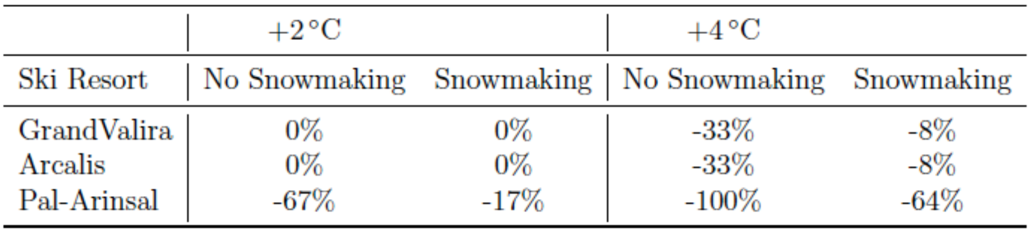
Once the model has created the daily number of agents and assigned a value to their attributes, the agent checks if the assigned ski resort is open or closed. If it is open, the agent moves to the ski resort. Otherwise, in this first version of the model, the agent leaves the country because there is no opportunity to ski in the selected ski resort. When all the agents have performed the decision making process the model computes the daily number of skiers at each ski resort and their total expenditure during the day. Finally the agents update their length of stay decreasing one day the value of this attribute. The agents with a new value of 0, that is, those that were one-day visitors or in the last day of their stay leave the simulation. In order to simulate a standard winter season, each time step in the model represents 1 day and simulations run for 151 days, from December 1st to April 30th, an entire winter season in Andorra.

3. Results

Four different scenarios have been run in order to analyze the future impact of climate change-induced snow reductions on the Andorra ski industry. The two first scenarios assume an increase of the mean temperature of +2 °C (P2) and +4 °C (P4) respectively. The other two scenarios add the effect of the potential snowmaking on enhancing the natural snow cover and extending the season in the +2 °C (P2SM) and +4 °C (P4SM) base scenarios. The resulting season length and number of skiers in the three ski resorts of Andorra (GrandValira, Arcalís and Pal-Arinsal) have been compared with the values of a reference period. The reference season length has been estimated as the average from 2000 to 2010 seasons and the reference attendance of skiers as the average of 2009 and 2010 seasons (Andorra Turisme 2010).

3.1. Impact on ski season length

During the reference season, the three ski resorts had an average season length between 139 and 146 days. In the P2 scenario only the ski resort of Pal-Arinsal, with most of its ski area at a lower elevation, around 2000 m, is affected by a 17% reduction of the season length, mainly at end of the season when snowfall is more erratic (Table 1). The other two resorts, with most of their ski area located at higher elevations (above 2200 m), are not affected by this particular climate change scenario. Comparing the results with the P2SM scenario it is noticed that the season reduction in Pal-Arinsal would be four times higher without snowmaking. In the P4 scenario all three ski resorts would suffer serious reductions in their ski season length. The Pal-Arinsal season would be dramatically reduced in half, whereas the GrandValira and Arcalís would suffer small season reductions (8%) at the end of the season. In the same way as P2SM scenario, P4SM shows that snowmaking would help to alleviate these reductions. However, because the worsening of climate conditions required to produce artificial snow, the capacity of snowmaking to extend the season under the +4 °C scenario is halved at Pal-Arinsal. Applying the 100-day rule, all three ski resorts would remain reliable in the with an increase of +2 °C, in the case of Pal-Arinsal, largely thanks to snowmaking. With an increase of +4 °C, Pal-Arinsal would not be reliable even with snowmaking, whereas the other two resorts would remain reliable thanks to snowmaking.



	+2 °C		+4 °C	
Ski Resort	No Snowmaking	Snowmaking	No Snowmaking	Snowmaking
GrandValira	0%	0%	-33%	-8%
Arcalis	0%	0%	-33%	-8%
Pal-Arinsal	-67%	-17%	-100%	-64%

Table 1: Projected changes in the ski season length.

3.2. Impact on the number of skiers and their expenditure

The use of an ABM model to simulate the interactions between the environment (snow cover) and the skiers makes it possible to connect the season length reductions at each ski resort with the drop of visitors at the regional scale in Andorra, and the related impact on expenditure in the country during a winter season. Table 2 shows the drop of the total number of skiers in Andorra under the different scenarios presented in the previous section. In the P2 scenario, a small drop of the number of skiers and their expenditure is noticed because only the lowest ski resort is affected on the first and last week of the season. On the other hand, the P4 scenario indicates a more severe drop (-20%) that would lead to a loss of skier-related revenue of approximately 50 M€ (value 2009) per season. In this case, the two ski resorts with higher visitor numbers (Pal-Arinsal and GrandValira) would be affected both at the beginning at the end of the season rising the extent of the impacts. Finally, if snowmaking had not been taken into account in the analyses, the impact of the loss of skiers and their expenditure would be much higher, -14% and -50% for the P2 and P4 scenarios respectively.

Scenario	No Snowmaking	Snowmaking
+2 °C	-14%	-1%
+4 °C	-50%	-20%

Table 2: Projected changes in the total number of skiers.

4. Discussion

The objective of this study was to understand the climate change vulnerability of the Pyrenean winter tourism industry by means of a georeferenced ABM. The findings of the study are congruent with previous literature analyzing the climate change impacts on the ski industry in other regions across the world. The reduction on the ski season length and the drop of the number of skiers has been projected especially on the lowest elevation ski resort in the region. Snowpack in the south-oriented central and eastern areas of the Pyrenees will be the most strongly affected by climate change (López-Moreno et al. 2009) turning Andorra ski resorts into a potentially vulnerable area despite their high location (most of the ski area is above 2000 m) in relation to other affected ski areas in Europe. On the other hand, snowmaking has a significant impact on extending and providing reliable season lengths in low elevation areas with a mid-range climate change scenario and in high elevation areas both with a mid and high-range climate change scenario. However, due to the projected increase of the minimum and average temperature the worsening of the required conditions to efficiently produce snow will become a future constrain. Therefore, in congruence with previous studies, snowmaking cannot completely solve the problem of ensuring snow cover at Andorra low elevation ski resorts and should be considered as a suitable short-term strategy, but not as a sustainable long-term adaptation strategy (Bark et al. 2010, Scott & McBoyle 2007, Steiger 2012). In addition to being climatically marginal, snowmaking could entail future constraints in terms of security in water supplies, ecosystems alteration and infrastructure and energy costs associated with large increases in snowmaking volumes. Even if they are climatically viable, these factors can turn snowmaking into an uneconomic adaptation strategy to some ski operators and unbearable in terms of carrying capacity for some other territories (Hahn 2004, Rixen et al. 2011, Scott & McBoyle 2007, Steiger & Mayer 2008).

Finally, as a first initial model, it is pertinent to note that the projected results should be taken as future general trends and not as accurate predictions for the Andorra ski resorts. This model will be adapted within a participatory planning process as a Planning Support tool involving and assisted by different stakeholders such as climate scientists, ski resorts managers and local planners and administrators. The tool will involve the different actors in a joint and transdisciplinary exercise to refine the model (Barnaud et al. 2008). Thus, it is expected the accuracy of the model outcome to be improved by discussing and refining the variables and parameters with the expertise of the stakeholders. Snow cover projections, the snowmaking module and the potential skier behavioral response are the main points to discuss and refine during this process. In this way, it is expected that not only the resulting model but also the discussion process could help the different stakeholders in understanding the vulnerability and the potential impacts as well as facilitate the decision-making process of designing and developing appropriate sustainable adaptation strategies to future climate change.

5. Conclusion

The georeferenced ABM methodology used in this study demonstrates potential as a tool to simulate the climate change impacts on the winter tourism and particularly to analyze the interaction between physical changes and socioeconomic implications. One of the most challenging issues in this kind of analysis is relating the projected physical impacts in ski areas to socioeconomic indicators, such as the shifts in skiers attendance or ski resorts revenues because a snow cover alteration (Dawson et al. 2009). One of the main reasons to use a georeferenced ABM was precisely to achieve a more detailed assessment of the socioeconomic dimension. The approach demonstrated here has potential to create and understand the linkage between the social and physical impacts relating the changes in the snowpack and resulting season length to the potential loss of skiers and their subsequent expenditure in the region. Moreover, compared to most of the models published to date, this methodology permits to include the behavioral response and the heterogeneity of the skier profile, very important issues to take into account in this type of studies. First, because individuals can easily change their skiing behavior as a result of changing snow conditions in comparison to the expense and difficulty to implement structural and management adaptation strategies in the ski resorts supply side Dawson et al. 2009). Secondly, in tourism modeling, visitors cannot be grouped as a single aggregated class with the same unique features. Tourists always perform different features and behavioral responses that should be included in the analysis to capture a more realistic understanding of the macro-level phenomena such are the impacts on a regional scale.

Future areas of refinement must focus on improving the heterogeneity of the agents (skiers) by including ski level or activity involvement and different behavioral response to environmental changes in basis of their profile. On the other hand, the use a georeferenced landscape made possible to capture the intrinsic spatial features of tourism phenomena. In our case, the ski resorts location and elevation has been taken into account with this approach. In this way, future developments must take into account the influence of other geographical parameters such as travel distances or specificities of the tourism destinations landscape such as slope orientation.

Finally, we are working to extend the model to other ski resorts in French and Spanish parts of the Pyrenees. This will allow the analysis of impacts at a regional scale, including the activity and spatial substitution of the skiers as well as other behavioral responses identified in previous studies (Behringer et al. 2000, Dawson et al. 2011, Fukushima et al. 2003, Hamilton et al. 2007, Pütz et al. 2011, Shih et al. 2009, Unbehaun et al. 2008).

Acknowledgements. The authors are thankful to Dr. Ignacio López-Moreno for share and support in climate projections data and to the Working Community of the Pyrenees (CTP) for financial support of this study. First author acknowledges also a predoctoral grant from Government of Andorra and Crèdit Andorrà Foundation, BTC2010/2011-0006-AND.

LITERATURE CITED

Abegg B (1996) Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen. vdf Zurich, Zurich

Abegg B, Agrawala S, Crick F, de Montfalcon A (2007) Climate change impacts and adaptation in winter tourism. In: Climate change in the European Alps: adapting winter tourism and natural hazards management. Paris: Organization for Economic Co-operation and Development

Andorra Turisme (2010) National Survey. Andorra Government

Anwar S, Jeanneret C, Parrott L, Marceau D (2007) Conceptualization and implementation of a multi-agent model to simulate whalewatching tours in the St. Lawrence Estuary in Quebec, Canada. Environ Modell Softw 22(12):1775-1787

Axtell RL, Epstein JM, Dean JS, Gumerman GJ, Swedlund AC, Harburger J, Chakravarty S, Hammond R, Parker J, Parker M (2002) Population Growth and Collapse in a Multi-Agent Model of the Kayenta Anasazi in Long House Valley. Proc Natl Acad Sci USA 99(3):7275-7279

Bark R, Colby B, Dominguez F (2010) Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. Climatic Change 102:467-491

Barnaud C, Bousquet F, Trebuil G (2008) Multi-agent simulations to explore rules for rural credit in a highland farming community of Northern Thailand. Ecol Econ

66:615-627

Beniston M (2003) Climatic change in mountain regions: A review of possible impacts. Climatic Change 59:5-31

Behringer J, Bürki R, Fuhrer J (2000) Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. Integrated Assessment 1(3).331-338

Berger T, Schreinemachers P (2006) Creating agents and landscapes for multiagent systems from random samples. Ecology and Society 11(2):19

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

Bithell M, Brasington J (2009) Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. Environ Modell Softw 24 (2):173-190

Bousquet F, Le Page C (2004) Multi-agent simulations and ecosystem management: A review. Ecol Model 76(3-4):313-332

Breiling M, Charamza P (1999) The impact of global warming on winter tourism and skiing: a regionalized model for Austrian snow conditions. Regional Environmental Change 1(1):4-14

CADS (2010) 2n Informe sobre el canvi climàtic a Catalunya. Consell Assessor per al Desenvolupament Sostenible. Generalitat de Catalunya

Chaix C (2010) Climate Change and tourism in the Alps: An analysis based on the pilot sites of the Alpine Space project ClimAlpTour. Université de Savoie. Institut de la montagne

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

Crooks AT (2010) Constructing and Implementing an Agent-Based Model of Residential Segregation through Vector GIS. Int J Geogr Inf Sci 24(5): 661-675

Dawson J, Scott D (2007) Climate change vulnerability in the Vermont ski tourism sector. Annals of Leisure Research 10(34):550-571

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

Dawson J, Scott D (2010) Systems analysis of climate change vulnerability for the US Northeast ski sector. Tourism Planning and Development 7(3):219-235

Dawson J, Havitz M, Scott D (2011) Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty. Journal of Travel and Tourism Marketing, 28(4):388-404

Deadman PJ, Robinson DT, Moran E, Brondizio E (2004) EFFects of Colonist Household Structure on Land Use Change in the Amazon Rainforest: An Agent Based Simulation Approach. Environment and Planning B: Planning and Design 31(5):693-709

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

Feuillette S, Bousquet F, Le Goulven P (2003) Sinuse: A multi-agent model to negotiate water demand management on a free access water table. Environ Modell Softw 18(5):413-427

Fukushima T, Kureha M, Ozaki N, Fujimori Y, Harasawa H (2003) Influences of air temperature change on leisure industries: case study on ski activities. Mitigation and Strategies for Climate Change 7:173-189

Galloway R (1988) The potential impact of climate change on Australian ski fields. In: Pearman G (ed) Greenhouse: planning for climatic change. CSIRO, Melbourne

Gimblett R, Skov-Petersen H (2008) Monitoring, Simulation, and Management of Visitor Landscapes. University of Arizona, Tuscon.

Grimm V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, Goss-Custard J, Grand T, Heinz SK, Huse G (2006) A standard protocol for describing individual-based and agent-based models. Ecol Model 198(1-2):115-126

Hamilton L, Brown C, Keim BD (2007) Ski areas, weather and climate: Time series models for New England case studies. Int J Climatol 27:2213-2124

Hahn F (2004) L'enneigement artificiel dans l'arc alpin: Rapport de synthèses. CIPRA Internationale Alpenschutzkommission. Available at www.cipra.org

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, Australia

Heo I, Lee S (2008) The Impact of Climate Changes on Ski Industries in South Korea In the case of the Yongpyong Ski resort. Journal of the Korean geographical society. 43(5):715-727

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

Itami R, Raulings R, MacLaren G, Hirst K, Gimblett R, Zanon D, Chladek P (2002) RBSim 2: Simulating the complex interactions between human movement and the outdoor recreation environment. In Monitoring and Management of Visitor Flows in Recreational and Protected Areas Conference Proceedings. Editors: Institute for Landscape Architecture and Landscape Management University of Agricultural Sciences, Vienna, Austria 191-198.

Janssen MA (2009) Understanding artificial Anasazi. Journal of Artificial Societies and Social Simulation 12

Johnson PA, Sieber RE (2009) Agent-based modelling: A dynamic scenario planning approach to tourism PSS. In S. Geertman, J., Stillwell (Eds.), Planning Support Systems: Best Practices and New Methods (pp. 211-226). Berlin: Springer

Johnson PA, Sieber RE (2010) An Individual-Based Approach to Modeling Tourism Dynamics. Tourism Analysis 15(5):517-530

Johnson PA, Sieber RE (2011) An Agent-Based Approach to Providing Tourism Planning Support. Environment and Planning B: Planning and Design 38(3):486-504

Keller F, Goyette S, Beniston M, (2005) Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. Climatic Change 72:299-319

Kohler TA, Gumerman GJ (1999) Dynamics in human and primate societies: Agent-based modeling of social and spatial processes. New York: Oxford University Press.

König U, Abegg B (1997) Impacts of climate change on tourism in the Swiss Alps. Journal of Sustainable Tourism 5(1):46-58

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

Ligmann-Zielinska A, Jankowski P (2007) Agent-based models as laboratories for spatially explicit planning policies. Environment and Planning B 34:316-335

Lipski S, McBoyle G (1991) The impact of global warming on downhill skiing in Michigan. East Lakes Geographer 26:37-51

López-Moreno JL, 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

Manson SM, Evans T (2007) Agent-based modeling of deforestation in southern yucatan, mexico, and reforestation in the midwest united states. PNAS 104(52): 20678-20683.

McBoyle G, Wall G (1987) The impact of CO2 induced warming on downhill skiing in the Laurentians. Cahiers de géographie du Québec 31(82):39-50

McBoyle G, Wall G (1992) Great Lakes skiing and climate change. In: Gill A, Hartmann R (eds) Mountain resort development. Centre for Tourism Policy and Research, Simon Fraser University, Burnaby, British Columbia, Canada.

Moen J, Fredman P (2007) Effects of Climate Change on Alpine Skiing in Sweden. Journal of Sustainable Tourism 15(4):418-437

Parker DC, Berger T, Manson S, McConnell WJ (2001) Agent-Based Models of Land-Use and Land-Cover Change. LUCC Report Series 6(1)

Parker DC, Manson S, Janssen MA, Hoffmann MJ, Deadman P (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann Assoc Am Geogr 93(2):314-337

Parrott L, Chion C, Martins CCA, Lamontagne P, Turgeon S, Landry JA, Zhens B, Marceau DJ, Michaud R, Cantin G, Ménard N, Dionne S (2011). A decision support system to assist the sustainable management of navigation activities in the St. Lawrence River Estuary, Canada. Environ Modell Softwa 1-16. DOI: 10.1016/j.envsoft.2011.08.009.

Perez L, Dragicevic S (2010) Modeling mountain pine beetle infestation with an agent-based approach at two spatial scales. Environ Modell Softw 25(2):223-236

Pütz M, Gallati D, Kytzia S, Elsasser H, Lardelli C, Teich M, WAltert F, Rixen C (2011) Winter Tourism, Climate Change, and Snowmaking in the Swiss Alps: Tourists' Attitudes and Regional Economic Impacts. Mt Res Dev 28:292–298

Rixen C, Teich M, Lardelli C, Gallati D, Pohl M, Pütz M, Bebi P (2011) Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential. Mt Res Dev 31(3):229-236

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. Climate Res 23:171-181

Scott, D, McBoyle, G., Mills, B., Minogue, A (2006) Climate change and sustainability of ski-based tourismin eastern North America: A reassessment. Journal of Sustainable Tourism 14(4):376-398

Scott D, McBoyle G (2007) Climate change adaptation in the ski industry. Mitigation and Adaptation Strategies to Global Change 12(8):1411-1431

Scott D, McBoyle G, Minogue A (2007) The implications of climate change for the Qubec ski industry. Global Environmental Change 1:181-190

Scott D, Dawson J, Jones B (2008) Climate change vulnerability of the US Northeast winter recreationTourism sector. Mitigation Adaptation Strategies for Global Change 13:577-596

Shih C, Nicholls S, Holecek DF (2009) Impact of weather on downhill ski lift ticket sales. Journal of Travel Research 47(3):359-372

Smajgl A, Heckbert S, Ward J, Straton A (2009) Simulating impacts of water trading in an institutional perspective. Environ Modell Softw 24(2):191-201

Smajgl A, Brown DG, Valbuena D, Huigen MGA (2011) Empirical characterisation agent behaviours in socio-ecological systems. Environ Modell Softw 26:837-844

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

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

Töglhofer C, Eigner F, Prettenthaler F (2011) Impacts of snow conditions on tourism demand in Austrian ski areas. Clim Res 46:1-14

Torrens PM (2003) Cellular Automata and Multi-agent Systems as Planning Support Tools. In Planning Support Systems in Practice Eds S Geertman, J Stillwell (Springer, Berlin) 205-222.

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

Unbehaun W, Probstl U, Haider W (2008) Trends in winter sports tourism: Challenges for the future. Tourism Review 63(1):36-47

World Tourism Organization WTO (2003) Climate change and tourism. Proceedings of the First International Conference on Climate Change and Tourism.

Djerba

Wilensky U (1999) NetLogo (and NetLogo User Manual), Center for Connected Learning and Computer-Based Modeling, Northwestern University. Available at http://ccl.northwestern.edu/netlogo/

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

Yang J, Wan C (2010) Progress in Research on the Impacts of Global Climate Change on Winter Ski Tourism. Advances in climate change research 1(2):55-62

A georeferenced agent-based model to analyze the climate change impacts on ski tourism at a regional scale

Marc Pons[a,b*], Peter A Johnson[c], Martí Rosas-Casals[b] and Eric Jover[a]

[a]Observatori de la Sostenibilitat d'Andorra, Sant Julià de Lòria, Andorra; [b]Sustainability Measuring and Modelling Lab, Universitat Politècnica de Catalunya, BarcelonaTech, Terrassa,Barcelona, Spain;
[c]Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada

(Received 21 January 2014; final version received 1 June 2014)

ABSTRACT

One main argument for modeling socio-ecological systems is to advance the understanding of dynamic correlations among various human and environmental factors, including impacts and responses to environmental change. We explore the shift in skier distribution amongst ski resorts taking into account the behavioral adaptation of individuals due to the impact of climate change on snow conditions. This analysis is performed at a regional scale by means of a coupled gravity and georeferenced agent-based model. Four different scenarios are considered. Two scenarios assume an increase of winter mean temperature of +2°C and +4°C respectively, taking into account only natural snow conditions. Two additional scenarios add the effect of snowmaking to enhance the natural snow depth and extend the skiing season in the +2°C and +4°C base scenarios. Results show differing vulnerability levels, allowing the classification of ski resorts into three distinct groups: (1) highly vulnerable ski resorts with a strong reduction in visitors attendance for all climate change scenarios, characterized by unfavorable geographical and attractiveness conditions, making it difficult to ensure snow availability in the future; (2) low vulnerability ski resorts, with moderate reduction in season length during a high climate change scenario but no reduction (or even an increase) in a low one, characterized by ski resorts with a medium capacity and attractiveness to ensure enough snow conditions and capture skiers from other ski resorts; and (3) resilient ski resorts, with good conditions to ensure future snow-reliable seasons and outstanding attractiveness, allowing them to offer longer ski seasons than their competitors and potentially attracting skiers from other closed or marginal resorts. Ski resorts included in this last group increase their skier attendance in all climate change scenarios. Although similar studies in the literature foretell a significant reduction of the ski market in the near future, another probable effect outlined in this study is a redefinition of this market due to a redistribution of skiers, from vulnerable ski resorts to more resilient ones.

Key words: Climate Change; Winter Tourism; Adaptation; GIS; Agent Based Model.

*Corresponding author. Email: mpons@obsa.ad

1. INTRODUCTION

One main argument for modeling socio-ecological systems is to advance the understanding of the dynamic correlations amongst various human and environmental factors, including impacts and responses to environmental changes. Examples come from a broad spectrum of spatial phenomena such as dynamics in ancient human and primate societies (Kohler et al., 1999, Axtell et al., 2002; Janssen, 2009), land use and land cover change (Manson and Evans, 2007; Parker et al., 2003), water management (Smajgl et al., 2009; Viaggi et al., 2009; Bithell and Brasington, 2009), residential segregation in urban contexts (Crooks, 2010) or insect outbreak spreading (Perez and Dragizevic, 2010). However, few studies have analyzed individual human and environmental interactions in tourism phenomena. Gimblett & Skov-Petersen (2008) and Itami et al. (2002) in particular, used ABM for the simulation and visualization of movement patterns of visitors in recreational landscapes, such as parks and protected areas. Johnson & Sieber (2009, 2010 and 2011) developed an ABM of tourism dynamics including travel, lodging and activity patterns. Regarding winter tourism, responses to environmental impacts and changes in tourism dynamics, Pons-Pons et al. (2012) developed a georeferenced ABM to analyze the climate change impacts on the ski winter tourism in Andorra and Balbi et al. (2013) used a spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. In recent years ABM models have been identified as a promising methodology to analyze tourism dynamics (Baggio, 2008). First, because they model and characterize interacting human-nature processes of heterogeneous individual behaviors that occur over space and time (Axtell, et al. 2002, 1996; Parker et al. 2003). In an ABM, tourist agents can be characterized with more realistic heterogeneous behaviors, governing activity, decision or accommodation preferences. For example, the visitor response if a ski resort were closed, as well as spatial characteristics, such as travel distances. Second, this approach is well suited for scenario development, data analysis, problem diagnosis and policy comparison (Ligmann-Zielinska & Jankowski, 2007; Johnson & Sieber, 2011). Since ABM facilitates the representation of individual-level spatio-temporal interactions, they have a relevance to representing and understanding the dynamics and characteristics of tourism.

Many studies dealing with tourism are focused on how climate change will affect the supply side of tourism, such as resorts, facilities or season days (Scott et al., 2003, 2008; Becken, 2005; Hoffmann et al., 2009; Steiger, 2010; Pütz et al. 2011). Many models analyzing climate change impacts on ski tourism base their estimations on physical snow models such as Abegg et al., (2007), Scott (2003), Uhlman (2009) or Steiger (2010). In these approaches, variables such as snow depth and duration of simulated snowpack are used to estimate the impact of climate change on the number of operational days (length of season). Some of these studies only model the natural snowpack at ski resorts (Uhlmann et al., 2009) or apply indicators such as snow cover days, defined as 2.5 cm of snow (Lamothe & Périard, 1988). This level of cover does not match with the reality of ski area operations that require 30-100 cm of snow to open a ski run. A few studies create statistical relationships between the length of season and snow depth or other climatological parameters (Moen and Fredmand, 2007). One of the major limitations of these studies using statistical models is the omission of the effect of snowmaking on future natural snowpack. This is the main limitation found in most of the previous literature analyzing the vulnerability of ski resorts (Scott et al., 2012). Studies that do incorporate snowmaking (Scott et al., 2003, 2008,; Hennessy et al., 2008; Steiger, 2010) found that impacts on ski resorts are lower than those reported by previous studies that only take into account natural snow. An alternate approach to these statistical and physical models is the analogue approach, where past and present experiences and responses to climatic variability, change and extremes provide insight for vulnerability to future climate change (Ford et al., 2010). This approach has been applied in North America (Scott, 2006; Dawson et al., 2009) and the Austrian region of Tyrol (Steiger, 2011), comparing the impact of climate change scenarios on season length. Most of these previous studies are focused on modeling supply-side impacts (ski operations) and none have explored how ski tourist demand has shifted in response to climate change impacts. Defining the mechanisms and variables related to tourists adaptation and behavior is an immediate research need to be filled. Even though recent studies point out that behavioral adaptation of tourists due to spatial, temporal and activity substitution could exert a strong influence on the final output of the climate change impact assessments (Behringer et al., 2000; Dawson et al., 2011, Gössling et al, 2012; Dawson et al., 2013), there is no analysis of this issue in the literature. This study proposes a new approach to better understand and explore how the potential behavioral responses identified in previous studies could affect the final outcome of climate change impact assessment. In addition to the identified behaviors and responses of tourists to climate change, this framework could be also applied to explore the influence of tourist behavior and responses to other factors that could affect their dynamics such as energy and transport issues or the influence of crowding in destinations, once this information has been gathered.

We explore the shift in tourist distribution amongst Pyrenean ski resorts taking into account the behavioral adaptation of individuals due to the impact of climate change on snow conditions. The Pyrenees is a mountain range comprising the northern portion of Spain, the southern portion of France and the small country of Andorra. Enclosing 49 alpine ski resorts, this region receives around 11 M skiers per year. Most of these skiers come from the surrounding regions. In Andorra, the most international destination in the Pyrenees, almost a 70% of the skiers come from the surrounding regions of Spain and France. This share is much higher in other ski resorts and turns the Pyrenees into a quite compact market with no significant competitors at close distances. In this context, the Pyrenees are highly dependent on winter tourism industry being their residents well aware that climate change is presented as a future threaten to snow availability and to future development of winter tourism related activities (March et al., 2014).

This analysis is performed at a regional scale by means of a coupled gravity and agent-based model (ABM). Unlike many models used to date, this methodology includes behavioral responses and heterogeneity of winter tourists. The use of a geo-referenced landscape makes it possible to capture the intrinsic spatial features of tourism phenomena, such as ski resort location and travel distances between them. In addition, the ABM model is linked to a gravity model: the potential redistribution of skiers among ski resorts when some of these have to close due to poor snow conditions, depends on the attractiveness of each ski resort and the travel distance between them.

The paper is organized as follows: in section 2, we present our model description following the "Overview, Design concepts and Details" (ODD) protocol (Grimm et al., 2006; 2010). Section 3 presents the model validation process Section 4 presents the specific scenarios generated in order to assess the vulnerability of the ski industry and the resulting outcome for each of these different projections Section 5 present and discusses the main findings of the paper, the suitability of the methodology, its limitations and the implications for further work. Finally section 6 presents the conclusions of this study.

2. MATERIALS AND METHODS

The "Overview, Design concepts and Details" (ODD) protocol, an accepted standard in ecological and social science literature, is used to formulate and describe the agent based model (Grimm et al., 2006; 2010). The overview component if this protocol provides an explanation about how the model is designed. Purpose, entities and attributes are then described to define the ABM. An entity is a distinct or separate object or actor that behaves as a unit in the ABM and may interact with other entities or be affected by the environment. The current state of the object is characterized by attributes. An attribute is a variable that distinguishes an entity from other entities of the same type or category, or traces how the entity changes over time. The design concepts depict the essential characteristics of the model. Finally the details section describes other information such as input data and submodels needed to understand, reimplement and replicate the model.

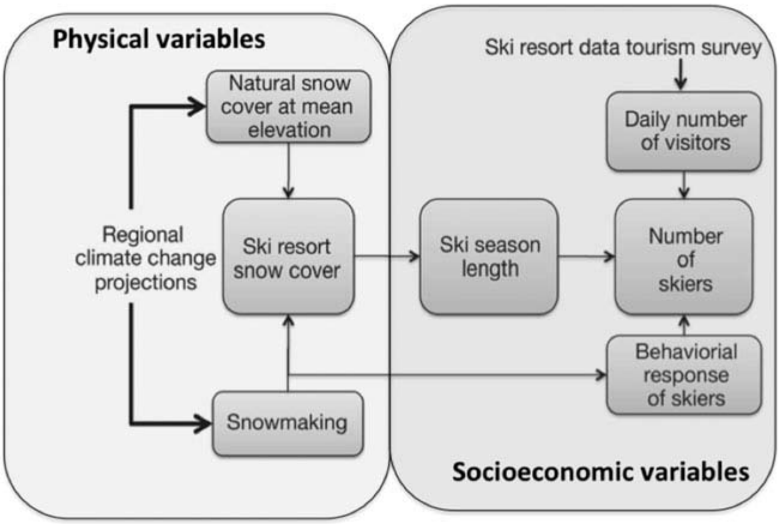


Figure 1. Conceptual map of the model linking the physical and the social variables.

Figure 1 shows the conceptual map of the model. Climate projections of future snow depth and potential snowmaking capacity at the mean elevation of the resort as well as the daily attendance of skiers at each ski resort are used as input data for the model. Using this information the model simulates by means of a gravity model and an ABM, the future ski season length and the daily attendance of skiers at each ski resort at a regional scale. As case study, the ski industry in the Pyrenean region, including France, Spain and Andorra is analyzed.

2.1 Overview

2.1.1 Purpose

The model is designed to explore questions about the shift in the skier distribution among ski resorts at a regional scale due to future climate change projections affecting local snow conditions at each individual ski resort.

2.1.2 Entities, state variables, scales and environment

In this model there are 2 main entities: skiers, the agents of our model, and ski resorts, which are fixed on the landscape. Skiers include the following attributes:

1) Assigned ski resort.
2) Current location: coordinates at each time step. This internal information helps the software to locate the agent at a ski resort on the map at each time step.
3) Adaptation strategy: whether skiers perform spatial or activity substitution when the ski resort is closed.

Ski resorts include the following attributes:

1) Location coordinates.
2) Season length in days.
3) State: whether the ski resort is open or closed.
4) Maximum capacity of daily skiers.
5) Attractiveness (described in more detail in the submodels section).

The simulation lasts for 151 time steps, the length of a standard winter season (from December 1st to April 30th), being the length of one time step equivalent to one day.

The environment, i.e. the space where the agents interact and respond to its changes, is implemented using two GIS layers: (1) the 41 main ski resorts of the Pyrenees (representing around the 92% of the total skiers (DSF, 2012; Biotti, 2013; ATUDEM, 2013; SkiAndorra) and (2) the main roads connecting the ski resorts (Figure2). The dimension of the points in this layer changes over time based on the daily attendance of skiers (the greater attendance the larger the point is shown) and the status attribute of each ski resort, that is, whether it is open (green) or closed (red) as a consequence of the daily projected snowpack conditions. The first 2 layers remain static during the simulation.

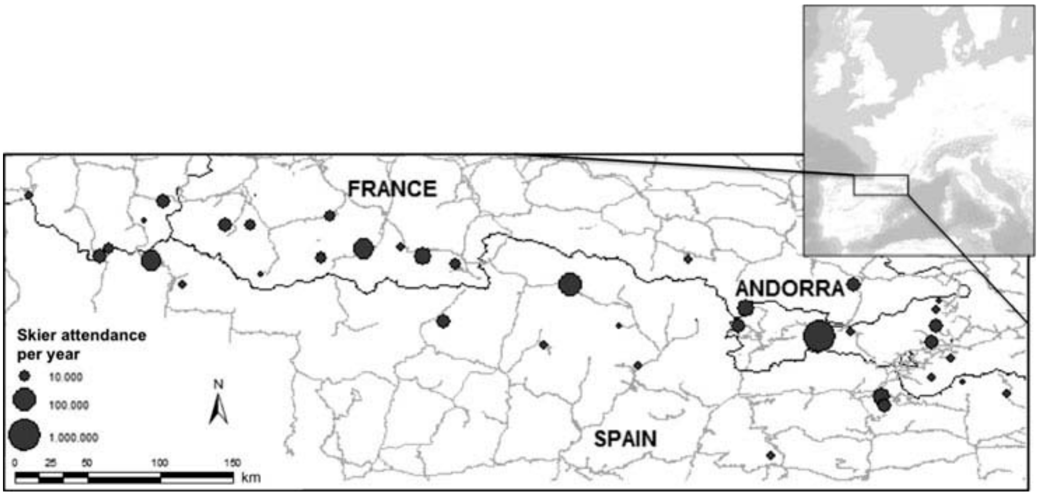


Figure 2. GIS layers with the location of the roads and the ski resorts of the Pyrenees. The size of the bullets represents the average skier attendance at each ski resort.

2.1.3 Process overview and scheduling

Using the snow cover projections and potential snowmaking days based on future climate scenarios as input data, the model starts simulating the projected season length at each ski resort and updating daily if it is open or closed during an entire winter season (Figure 3). The aim of this framework is to allow snowpack and ski days simulations to be used and integrated into the ABM regardless of modeling approach used. In our particular case for the Pyrenees, these variables have been simulated using the projected changes in the Pyrenean daily snowpack during the 21st Century by means of a Snow Energy Balance Model (SEBM) for the study area and coupled with technical parameters of ski resorts operation and snowmaking processes. Following the experience of technical staff in ski resorts, a daily minimum temperature threshold of -2°C has been used to compute the potential snowmaking days during a winter season. During these potential snowmaking days, it is assumed that 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 following these criteria. Therefore, a ski resort is considered open as soon as it reaches the 30 cm threshold considering both natural snow and snowmaking. This threshold is one of the most used criterions to assess the climate change vulnerability of ski resorts (Abegg, 1996; Scott et al. 2008; Steiger et al. 2010). In order to simulate the ski season length, those days with at least 30 cm of snow depth were those considered as open days. For a detailed description of the snow model used and the climate change projections see López-Moreno et al. (2009) and Pons-Pons et al. (2012). Snowpack projections are based on 2 future emissions scenarios: the IPCC SRES A2 and B2 scenarios for different altitudinal levels: 1500, 2000, 2500 and 3000 m. These scenarios project future climate change based on different assumptions for greenhouse gas emissions, land-use, economic and technological development and other diving forces (IPCC, 2007). In our study B2 and A2 were used as for mid and high climate change scenarios respectively.

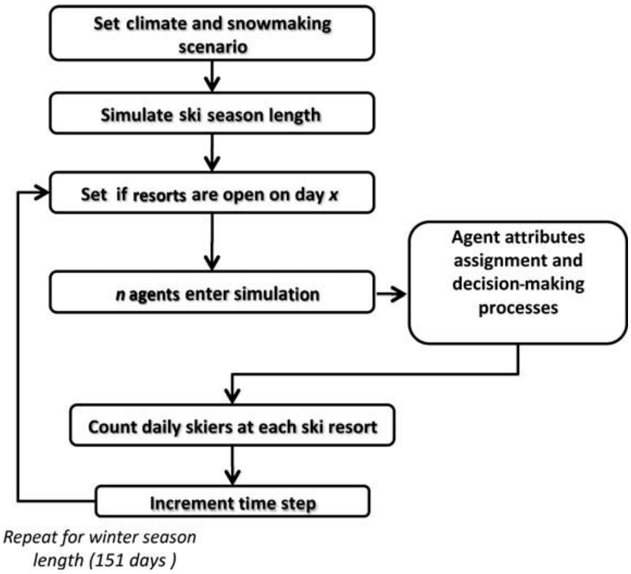


Figure 3. Model processes flowchart.

Based on ski resort statistics and survey data of tourism activity, the model assigns the initial number of agents at each ski resort on the basis of the current distribution of skiers over the studied region. With only aggregated information about skier visits available from official regional ski associations or administrations Statistics (DSF, 2013, ATUDEM, 2013, Botti, 2013), and also considering that many ski resorts do not easily or freely share skier numbers, deep research from more than 20 different local and regional newspapers, ski resorts periodical press releases and news websites was conducted to estimate the frequentation at 41 of the 49 ski resorts of the Pyrenees from 2008-2009 to 2011-2012. The remaining 8 ski resorts are very small ski areas (less than a couple or three of runs and a couple of ski lift, often presented as s complementary activity of a hotel or nordic ski resort) which information was not available. From this data, the average from the last 3 seasons was assigned as the average yearly skier visitation at each ski resort. To estimate daily attendance, a daily visitation curve of skiers was estimated in order to modulate the visitation based on holidays, weekends and working days. This issue is a crucial point to the model because the impact of reducing the ski season length is not the same if important holidays such as Easter or Christmas are affected (Steiger, 2013). The only information on tourist visits on a daily basis was provided by the national tourism survey from the Andorran Government and statistics from the national tourism department (Andorra Turisme, 2012) for the seasons 2008-2009 to 2011-2012. These surveys were used to develop the profile of the visitors and identify the daily number of skiers. Approximately 8000 visitors to Andorra respond to the national tourism survey every winter season and this information is linked to the observations of the total foreign vehicles entering the country. Table 1 shows the data and the sources used as input in the model.

Variable	**Source**
Snow depth projections	Lopez-Moreno et al. 2009
Coordinates of the ski resorts	GIS layer created by satellite imagery (ICC; SIGMA; Geoportail France; GoogleEarth)
Ski resorts yearly attendance from 2008-2009 to 2011-2012 seasons	Ski Andorra; Atudem, DSF; Press reports and newspapers
Total length of ski slopes	Ski resorts official webpage
Price of the day ski pass	Ski resorts official webpage
Complementary activities	Ski resorts official webpage
Vicinity to commercial area	GIS layer of cities and villages from France Andorra and Spain (ICC; SIGMA; Geoportail France; GoogleEarth)
Daily attendance curve of skiers	Andorra Turisme; Estadistica.ad

Table 1. Data and sources used in the model.

To explore the emergent macro-level phenomena from micro-level individual actions and local conditions of ski resorts, the model implements the adaptation behavior of skiers through spatial and activity substitution (defined in section 2.1.4). Different studies based on surveys (Behringer et al., 2000; Fukushima et al., 2002; Hamilton et al., 2007; Unbehaun et al., 2008; Dawson et al., 2011 and Pütz et al., 2011, Dawson et al, 2013) have identified the potential behavioral and adaptative response of skiers to poor snow conditions. On the basis of these results, the share of potential skiers performing a spatial and an activity substitution are identified and implemented in the model. Thus when a ski resort is closed, the decision-making process shown in Figure 4 is applied to each skier at a particular ski resort. These skiers perform an activity substitution and stop skiing when the ski resort where they would typically go skiing is closed. The rest of skiers perform a spatial substitution and are redistributed amongst the remaining open ski resorts in the region by means of a gravity model (described in depth in the submodels section) according to the attractiveness factor of each ski resort and the distance between the origin (in this study, the initially assigned ski resort) and the potential alternative resort.

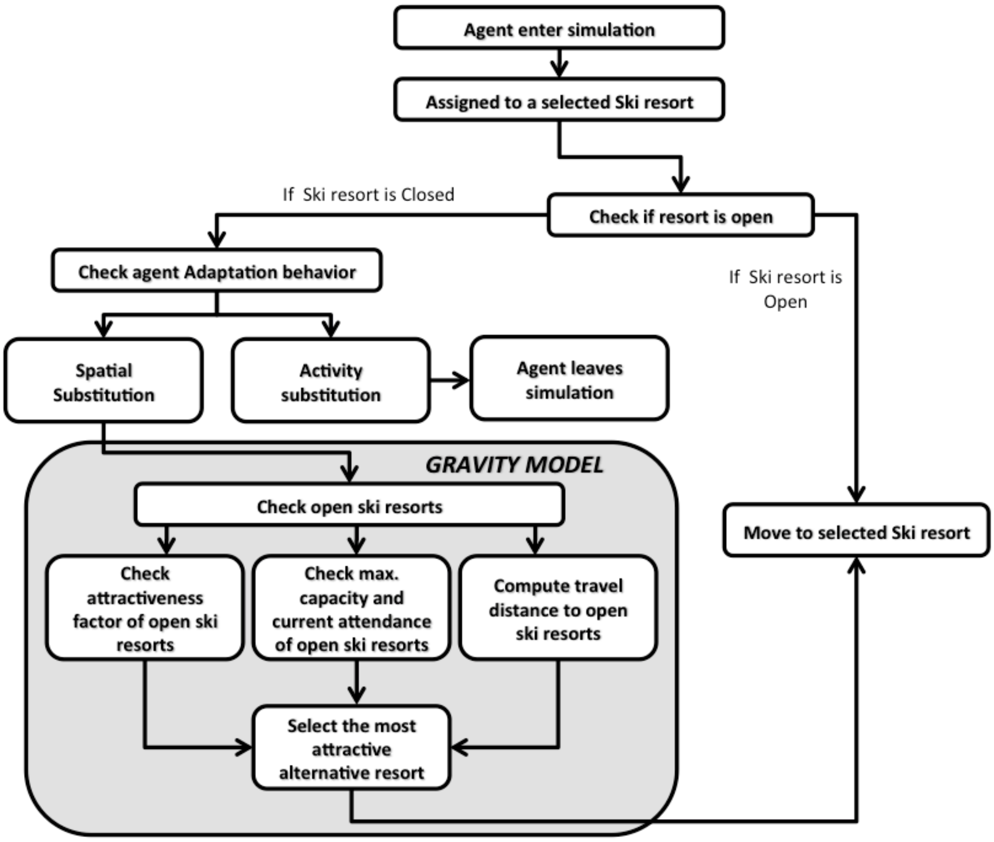


Figure 4. Agent decision-making flowchart.

2.1.4 Design Concepts

The basic principle addressed by this model is the emergence of potential shifts in the current skiers distribution at a regional scale due to changes in local snow conditions. This concept is addressed by checking how behavioral adaptation of skiers affects the attendance at the local ski resort level, and at the regional scale, by means of the simulation of the potential redistribution of skiers. Skier agents do not implement any learning or prediction capacity and base their decisions solely on the objective of finding a ski resort with suitable snow conditions to support skiing. To achieve this objective, agents are sensitive to four variables: (1) current snow conditions, (2) travel distance between ski resorts, (3) an attractiveness factor of each ski resort and (4) the maximum daily capacity to host skiers. A stochastic process is used to randomly assign the choice of the adaptive behavior (i.e., whether the skiers perform an activity or a spatial substitution). Based on current snow conditions (i.e., the resort is closed due to insufficient snow conditions) agents have a 5% probability to stop skiing. This probability is based on existing surveys (i.e. Behringer et al, 2000). Otherwise, skiers move to an alternate resort characterized by the gravity model (explained below). Movement to this alternate resort is restricted by its maximum capacity. From interviews with ski resort managers, this maximum capacity was assumed as twice the maximum daily attendance during the reference season (average from 2008/2009 to 2011-2012). This involves an indirect interaction between agents, affecting the selection of the final destination. In this initial version of the model, no collectives have been implemented. However in further versions collectives could be implemented in order to segregate the adaptation behavior and the preference choices of different profile of skiers such as expert skiers, beginners or families. These differences in preference and adaptation behaviors could also affect the potential redistribution of skiers among ski resorts.

To observe shifts in the distribution of skiers at a regional scale, three different variables are analyzed as model output on a daily basis and for each ski resort: (1) number of attracted skiers when open, (2) number of skiers lost when closed due to insufficient snow depth and (3) total seasonal skier attendance.

2.1.5 Initialization

The model is initialized for each future scenario with the projected season length of 151 days, with attendance based on the present regional distribution of skiers. The present average distribution of skiers has been calculated as the average of the historical data of attendance for the winter seasons from 2008-2009 to 2011-2012.

2.1.6 Input data

The input data of the model are (1) the current daily distribution of skiers at each ski resort and (2) the days with sufficient snow depth (30 cm indicator), in order to compute the season length during a winter season in different climate scenarios.

2.1.7 Submodels

A gravity model, in analogy with Newton's gravity law, is used to analyze the potential redistribution of skiers (spatial substitution) among the ski resorts of the whole region based on both the attractiveness of each ski resort and the travel distance between them when some ski resorts have to close due to poor snow conditions.

Introduced in its contemporary form in 1946 (Zipf, 1946), but with roots that go back to the eighteenth century (Monge, 1781), the gravity law is a spread framework to predict population movement (Monge, 1781; Jung et al. 2008; Thiemann et al. 2010) cargo shipping volume (Isard, 1960; Kaluza et al., 2010), inter-city phone calls (Krings et al., 2009), bilateral trade flows between nations (Pöyhönen, 1963) or migration processes (Kararema et al, 2000), just to name a few. The basic principle governing these models is that the shorter the distance between two objects and bigger their mass, the greater the gravitational pull between these two objects. Following this principle, the gravity law assumes that the number of individuals that move between locations i and j is proportional to the mass, i.e. the population of the source and inversely proportional to the distance to the potential destinations.

The model we describe estimates the total number of skiers moving from a closed ski resort i to an open ski resort j (F_{ij}) on the basis of an attractiveness factor (i.e., mass) of the potential destination resort (G_j) and the inverse of the distance between the origin i and destination resort (D_{ij}), affected by a unique parameter $\langle$ (Eq. 1).

$$F_{ij} = G_j / D_{ij}^{\ \alpha} \qquad \text{Eq.1}$$

The attractiveness factor represents the capacity of each ski resort to attract skiers to their facilities. The create this submodel characterizing this feature, a non-parametric statistical analysis was carried out using a set of 15 physical and socio-economical variables that characterize the ski resorts. Amongst all variables, four were found to be the most significant in explaining the current redistribution of skiers (p-value < 0.05). A multiple regression model was used to identify the main variables that affect the current capacity to attract skiers and explain the present distribution in the region (Eq. 2). The model used, permits to explain almost 90% of the current distribution of skiers on the Pyrenean region ($R^2 = 0,87$; p-value < 0,001) based on four variables: (1) total length of ski slopes, (2) the mean cost of the all season daily adult ski pass, (3) whether or not the resort offers complementary activities to skiing, and (4) its location, near or distant from a large commercial area. This last qualitative binary variable assigns a value of 1 to those resorts with a commercial area (not only isolated stores) within a radius of 25 km. This indicator permits to identify those resorts with the ability to offer shopping as a complementary activity, a factor identified to have a high influence on tourists when choosing a ski resort (Andorra Turisme, 2012). All these factors are congruent with previous work that identified, through survey research, the most influential factors when choosing a ski destination (Dawson, 2009).

$$\begin{aligned} Attraciveness\ Factor \ = \ & \beta_1 * Total\ Lenght\ km\ of\ slopes + \ \beta_2 * mean\ daily\ ski\ pass \\ & + \beta_3 * Complementary\ activities + \ \beta_4 * near\ a\ commercial\ center \end{aligned}$$

Eq. 2

By applying the gravity model when a given resort it has to close because of poor snow conditions, we calculate the potential number of skiers that will shift from the closed ski resort to the remaining open resorts. For instance, as Figure 5 shows, if the resort of La Molina is closed (in black), the biggest share of its skiers (46%) will shift to the nearest ski resort, Masella, due to the effect of the distance variable. However, due to the different attractiveness of the resorts, a share of the skiers will move to a further resort. Despite being much further away from La Molina, Grandvalira receives a significant share (11%), because of its high attractiveness factor.

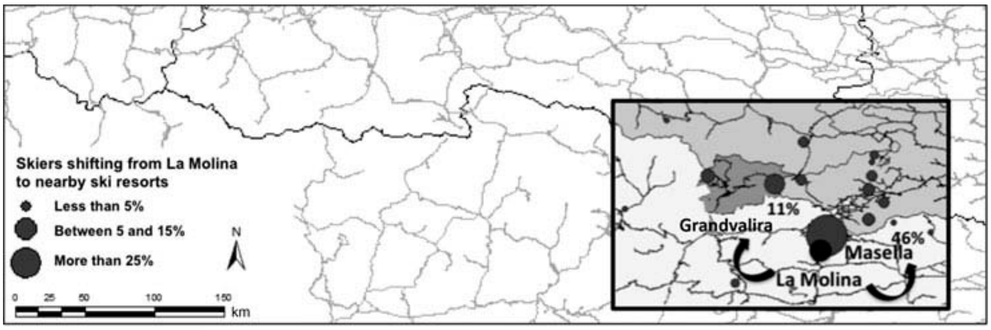


Figure 5. Gravity model applied to the skiers of La Molina when it is closed. The size of the dots represents the percentage of skiers shifting from La Molina (black dot) to nearby resorts.

3. VALIDATION

One challenge of this modeling approach is the validation process of the model results. Here we use an analogue approach (Dawson et al., 2009) to corroborate our results, since the outcome of the model are simulations of future skiers attendance based on projected ski season reductions. This approach looks for a past winter season with analogous climate conditions that could reproduce a similar situation as the projected future winter season. However, the low frequency in the occurrence of years with analogous conditions to future climate scenarios and the scarcity of detailed historical data on skiers attendance makes it difficult to carry out a good validation process. In this sense, the 2011-2012 season was found to be the one in the last ten years performing the closest climate situation to the +2°C scenario. During this season, the average minimum temperature in Andorra was 2.2°C over the value for the control period (1961-1990), most similar to the +2°C scenario. Thus, the +2°C with snowmaking scenario results are compared to the 2011-2012 skiers attendance, as a form of validation.

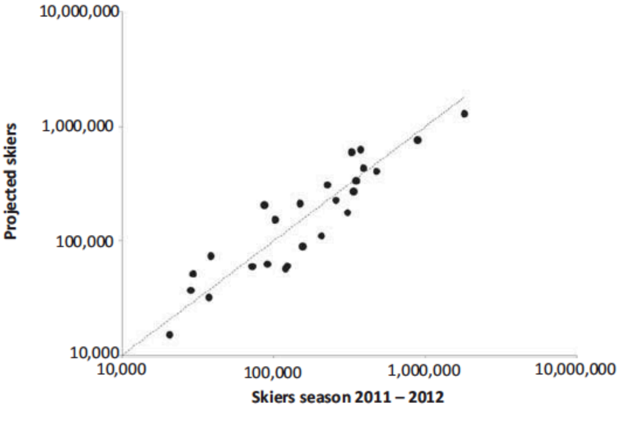


Figure 6. Correlation between real skiers for the season 2011–2012 and projected skiers in the +2°C scenario.

Figure 6 shows correlated values between projected skiers in the +2°C The model explains remarkably well the real data behavior and no deviation trends are observed. In the resorts where the anomaly of temperature in the analogous year is closer to the projected scenario (central-eastern part of the Pyrenees) the observed error is less than 30%. The error can be explained partly by three main sources:

1) Regional climatic models: there exists a lack of spatial resolution and an inherent uncertainty associated with regional climate models (Alexandru et al., 2007).
2) Quality and quantity of historical data on skiers attendance are not always complete or the desired spatial scale.
3) The model cannot explain temporal substitution (i.e., those skiers not performing spatial substitution, but shifting their skiing season depending on snow availability).

This validation process could be used to assess the usefulness of the gravity approach (eq. 1). This method relies on adjustable parameters to fit empirical data that vary from region to region (Isard, 1960). In this sense, distance D_{ij} is one of the main variables that can be tuned by means of an exponent α (i.e. D_{ij}^{α}). The best fit result is obtained with $\alpha = 0$ ($R^2 = 0.999$), which implies that, in this particular case study, the distance is not a factor having a huge impact on the total distribution of skiers in a future climate change scenario (Figure above). This is mainly due to the fact that in a future climate change scenario only few resorts remain available (the ones with already the highest frequentation). Redistribution options for skiers are reduced and so is sensitivity to alpha in D_{ij}^{α}. Thus, the effect of distance is hidden because the amount of skiers shifting to these resilient resorts is low regarding the current high frequentation of these ones. Even though distance effect has not a significant impact on the total distribution, it actually has an impact on the reallocation of skiers (skiers moving because ski closures) shifting from one ski resort to another one. Furthermore, a limitation in this study is that the distance considered is not the distance from the skier home origin to the potential destination but rather the distance between potential destinations. When the model is run under less severe conditions (i.e., both more homogenous attractiveness and heterogeneous variability in the projected season length reduction), α becomes a significant parameter (results not shown in the article). Therefore, α it should be considered and properly tuned in order to apply this model to other regions.

4. RESULTS

Four different scenarios were run to analyze the redistribution of future skiers among the Pyrenean ski resorts induced by climate change-related snow reductions. The two first scenarios assume an increase of the winter mean temperature of +2°C and +4°C respectively, taking into account only natural snow conditions. The other two scenarios add the effect of the potential snowmaking on enhancing the natural snow depth and extending the ski season length in the +2°C and +4°C base scenarios.

Figure 7 shows the attractiveness factor and the projected number of skiers in a present mean winter season and for two future scenarios: assuming an increase of +2°C and +4°C of the winter mean temperature and taking into account only the natural snow depth to compute the ski season length. Two different groups of ski resorts with different attendance patterns can be identified. For most of the ski resorts (≈ 70%), a slight decrease in skier attendance, less than 25%, is projected for a +2°C scenario and a significant decrease, between 50% and 100%, for the +4°C scenario. However, only few resorts are able to increase the number of visitors in both future scenarios due to both a lower climatic vulnerability and a higher touristic attractiveness compared to their competitors. On the other hand, the current relationship between the attractiveness factor of the ski resorts and the total attendance of skiers per year is almost linear (black line in Figure 7). In a climate change-induced future, this relationship becomes increasingly non-linear (dashed line in Figure 7).

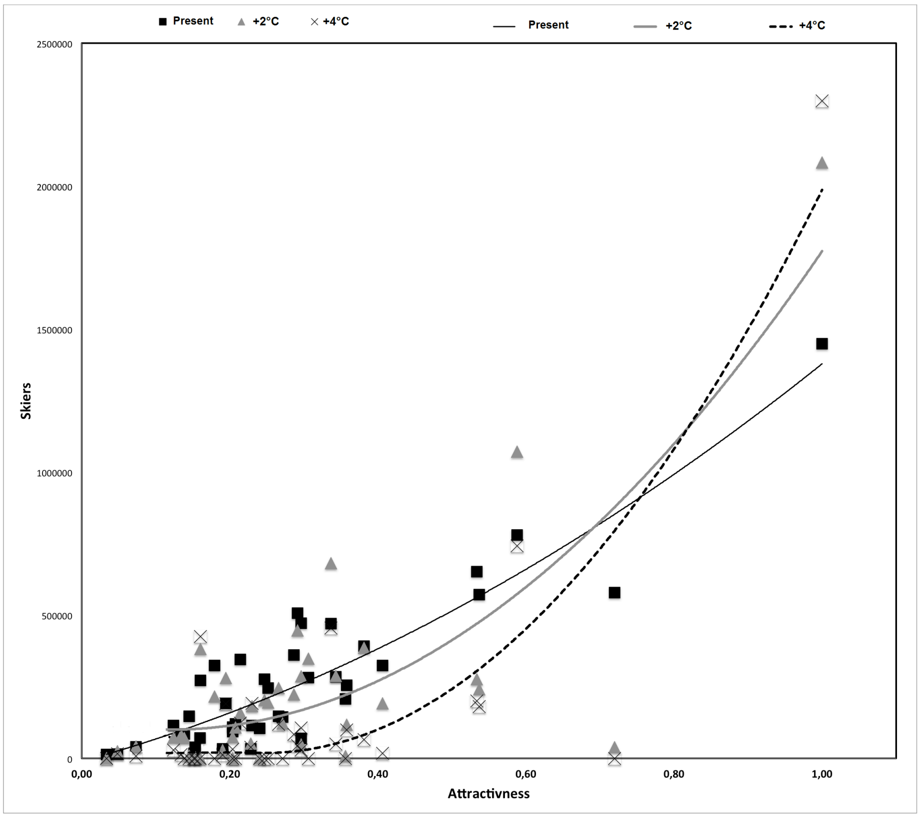


Figure 7. Attractiveness factor and changes in the total number of skiers for each ski resort in three different scenarios: a mean present winter season and assuming an increase of +2°C and +4°C of the winter mean temperature.

Figure 8, shows the attractiveness factor and the projected number of skiers in a present mean winter season and for two future scenarios: assuming an increase of +2°C and

+4°C of the winter mean temperature and taking into account the capacity of snowmaking to increase season length.

In this case, three different groups of ski resorts can be identified based on the projected changes to skier attendance and resort attractiveness. The first group of resorts (Figure 10), characterized with a low attractiveness index value, show a slight reduction in future attendance for the +2°C scenario, and in some cases keeps the current attendance of skiers. With this group of resorts, despite taking snowmaking into account, significant decreases in skier visitation are projected for the +4°C scenario. The second group of ski resorts, generally with a medium attractiveness index value, are able to increase their attendance in the +2°C scenario but not in the +4°C, where decreases are projected. Finally, the third group, typically with a higher attractiveness index, shows opposite behavior to the first group, being able to increase future attendance in both scenarios. This demonstrates an outcome of highly attractive ski resorts consolidating their dominant position at the expense of less attractive ski resorts, that may be struggling to adapt to changing snow conditions. Figure 9 shows an example of a ski resort classified in this third, 'resilient' group with a high attractiveness index and privileged geographical conditions. This resort has a high capacity to attract the skiers from the more vulnerable resorts located in the surrounding area. However, in snowmaking scenarios, the capacity to attract is reduced. In the +2°C scenario with snowmaking, the vulnerability of surrounding ski resorts is lower and therefore competitiveness is more evenly distributed among resorts. In the +4°C scenario with snowmaking this effect is not as evident due to the reductions of the potential snowmaking days.

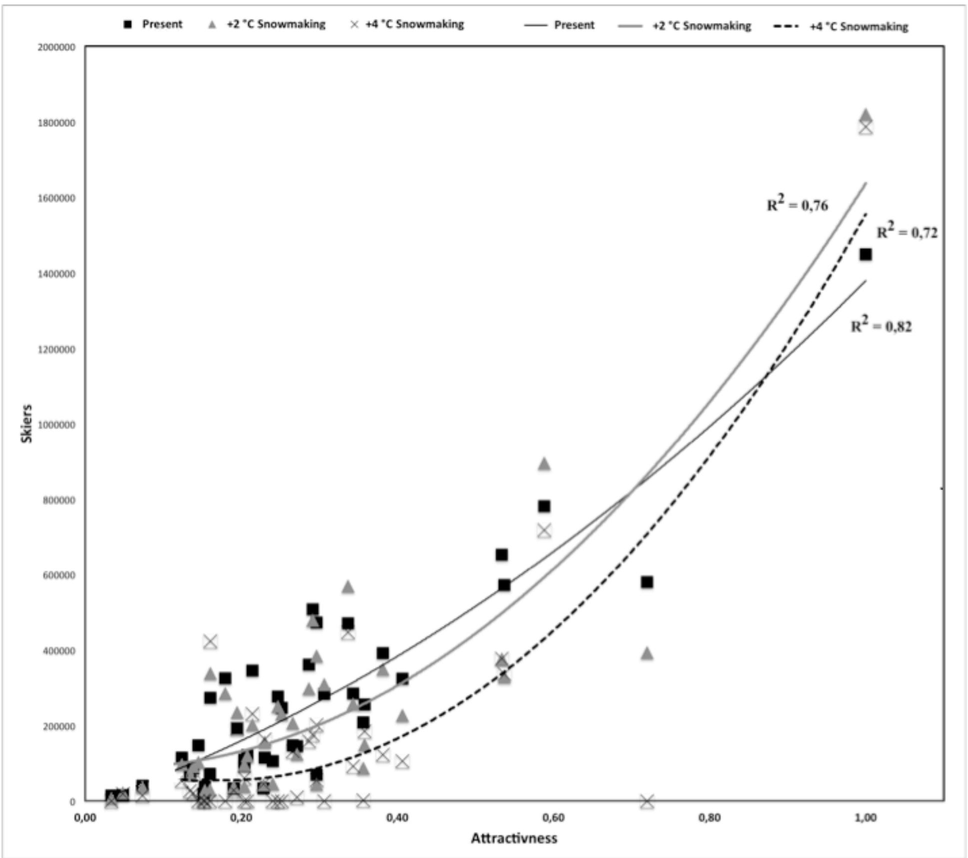


Figure 8. Attractiveness factor and changes in the total number of skiers for each ski resort in three different scenarios: a present winter season and assuming an increase of +2°C and +4°C of the winter mean temperature taking into account the contribution of snowmaking.

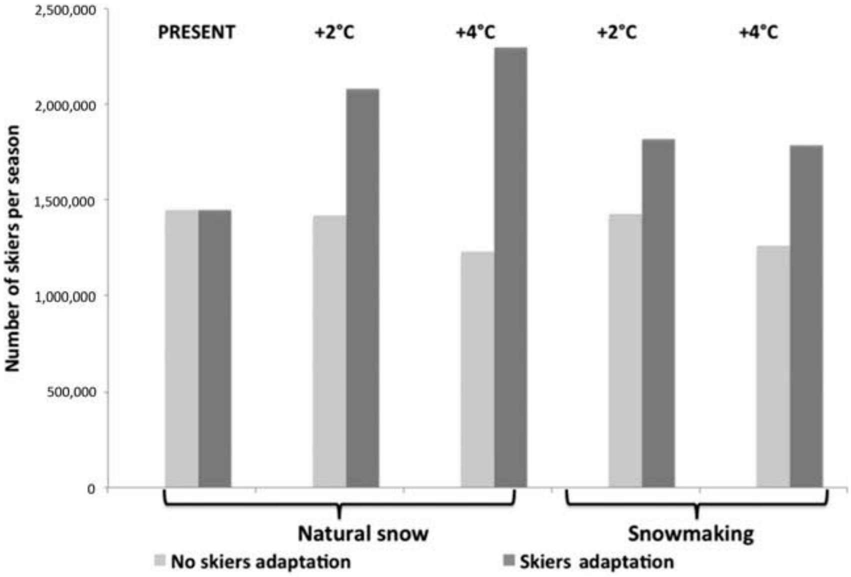


Figure 9. Yearly skier attendance in a resilient ski resort in different climate change scenarios with and without behavioral adaptation of skiers.

Regarding the relationship between the attractiveness factor and the total skier attendance in future climate change scenarios, a non-linear pattern is also observed when considering the effects of snowmaking (Figure 8). However, although increases in skier attendance are seen with every increase in attractiveness factor, snowmaking leads to a flattening of the curves with respect to the natural snow scenario, mainly in the +2°C scenario. In the case of the +4°C scenario, this effect is less significant since in a high climate change scenario, the effect of the snowmaking to enhance the season length is lower due to fewer potential snowmaking days available in the Pyrenean ski resorts. This change from an almost linear to an exponential relationship between the attractiveness and the total attendance of most of the analyzed ski resorts, results in an increase of the distance between the resilient and the vulnerable ski resort groups.

Figure 10 shows the clustering of the analyzed ski resorts in the 3 identified groups: the resilient ski resorts, the low vulnerability ski resort and high vulnerability ski resorts (only some ski resorts are shown in order to make the figure and the interpretation of the groups more clear).

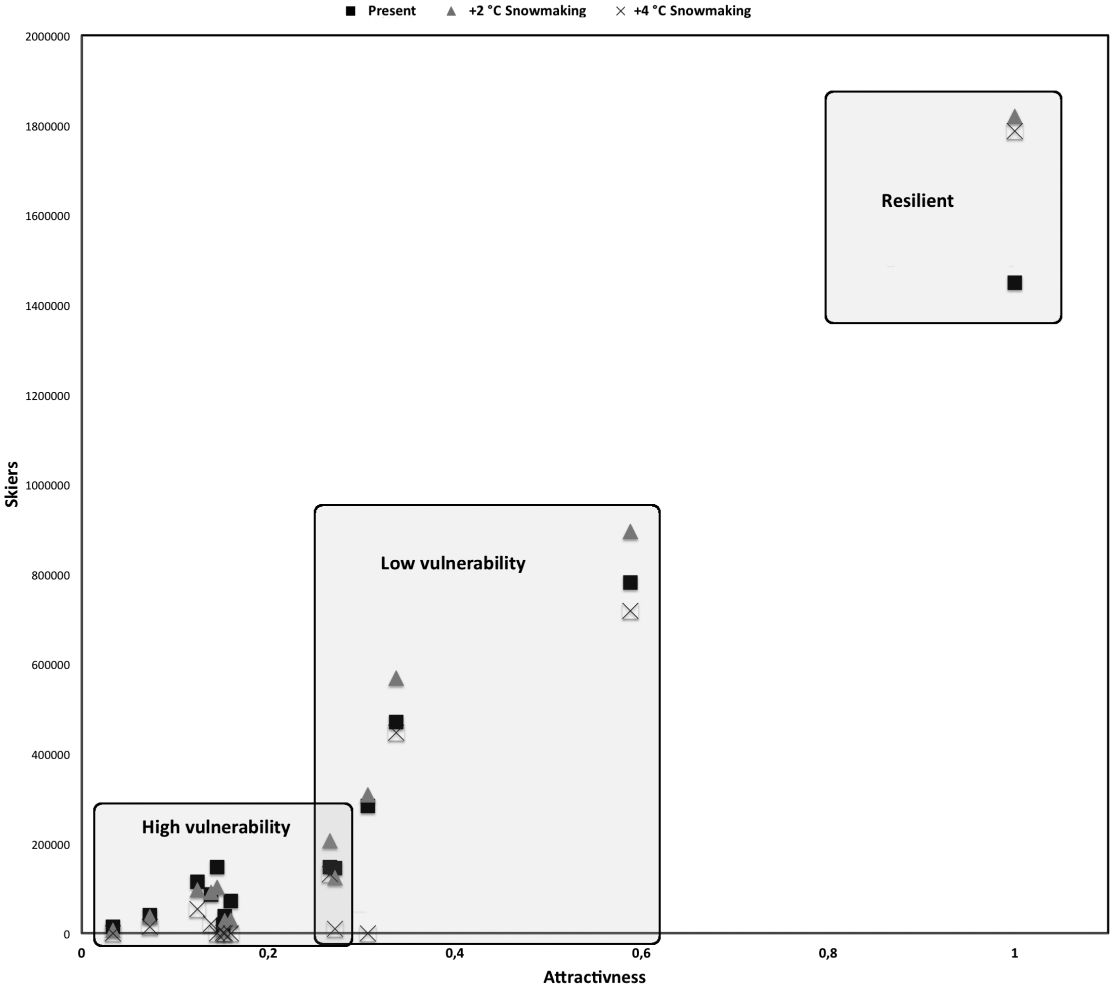


Figure 10. Clustering of the ski resorts in three groups: high vulnerable, low vulnerable, and resilient.

5. DISCUSSION

The aim of the model presented here is to support an exploration of shifts in skier distribution amongst ski resorts at a regional macro-scale, due to changes in local snow conditions as a result of future climate change projections. To date, all studies analyzing the climate change impacts on ski resorts have assessed the potential reductions of skiers separately for each ski resort. This previous approach led in all the projected scenarios to a decrease in skier attendance for all the ski resorts (i.e., Scott et al. 2003, 2008, Dawson et al. 2009, Steiger 2010, Pons-Pons et al. 2012). In contrast with these studies, this approach presented here shows that the vulnerability of the ski resorts within the same geographical region can be affected by the response of skiers to poor snow conditions. The agent-based model permitted the inclusion of the individual behavioral response of skiers by means of an activity or spatial substitution when their typically frequented ski resort was closed due to poor snow conditions.

Results from this analysis are used to classify the ski resorts in three different groups. A first group consists of highly vulnerable ski resorts that will suffer an attendance reduction on its attendance of visitors in both mild and strong climate change scenarios. This group is usually characterized by conditions that make it difficult to ensure a snow-reliable season, such as low elevation (Steiger, 2010; Pons-Pons et al, 2012), south oriented areas, with a predominant Mediterranean influence (Lopez-Moreno et al., 2009) and also a low touristic attractiveness compared to other nearby competitors. A second group consists of low vulnerability ski resorts that will suffer a reduction in attendance under a strong climate change scenario, but not in a mild one, where these resorts would keep their current level of skier attendance or even increase it. This group is usually characterized by ski resorts with medium capacity to assure enough snow and a medium attractiveness factor to capture skiers from other closed ski resorts. Lastly a third group consists of resilient ski resorts, with good conditions to assure future snow availability (high elevations, north oriented slopes, more Atlantic influence (López-Moreno et al., 2009) and with a high attractiveness factor, which makes them able to offer longer ski seasons than their competitors and to attract skiers from closed ski resorts. Ski resorts classified in this group will increase their skier attendance in both low and high climate change scenarios. A new variable, the attractiveness of each ski resort, was included in the analysis of the climate change impacts on the winter tourism. By means of a gravity model, this variable, characterized by structural and supply features of each ski resort, allows, together with distances between ski resorts, to project the potential redistribution of skiers. This attractiveness factor is found to affect the vulnerability of each ski resort. Ski resorts able to offer longer ski seasons compared to other ski resorts, plus having a high attractiveness factor are considered to be the most resilient to climate change impacts.

The second parameter of the gravity model, the travel distance between ski resorts was found not to have a huge impact in the particular case study of the Pyrenees. In this case, the shifting options for skiers, and consequently the sensitivity to alpha in

Dij^{α}, are highly reduced due to the resulting configuration of vulnerable and resilient ski resorts to climate change. This is because the redistribution is performed mainly and only among the limited resilient resorts, which also stand as the more attractive ones and with already a high attendance on comparison with the attracted skiers. However, when testing the model sensitivity to α under less severe conditions (i.e., homogenous attractiveness and variability in the projected season length reduction), this variable becomes a significant parameter to take into account in the model. Therefore, it has to be considered to apply this model to other regions and correctly calibrate the model.

Due to the low frequency in the occurrence of years with analogous conditions to future climate scenarios and the scarcity of detailed historical data of skier attendance at each ski resort, the validation of the model results is a central challenge to the modeling process. Despite this constraint, the error of the model is acceptable for a first stage of development. There are several key sources of error that can affect the model outcomes. First, there is inherent error of the snow cover regional model used and its resolution to capture enough local variability. Second, because of high competition between ski resorts, there is limited availability of the skier attendance data, and its reliability should be questioned. This unreliability of resort-sourced data is an issue that could compromise the comparison of projected skiers attendance with the analogous year. Finally, since there is no Pyrenean survey so far capturing the adaptive behavior of skiers when confronted with poor snow conditions, results of surveys from different studies in the Alps (Behringer et al., 2000) and USA (Dawson, 2011) were used. In addition to the share of temporal substitution, not taken into account in this study, this issue could also introduce a significant error to the model because the dynamics and the response of the Pyrenean tourists may be different.

Future areas of refinement of this work will focus on reducing the error of the model and improve the accuracy of the projected results. To achieve this we are working to create and use snow cover models with higher spatial resolution, able to better capture the regional variability at a local scale in the future snow depth of each ski resort. Additionally, a survey will be designed and carried out to capture the behavioral response of visitors when facing poor snow conditions for the Pyrenees region. Moreover, the segregation of different adaptative behaviors based on different skier profiles and the influence of the future scarcity of resources like fuel or water, or the effect of crowdedness will be considered in order to analyze potential sensible variables that could constraint the ski industry. One of the main limitations of the current model version is the use of the distance. The suitable distance to consider when modeling skiers redistribution should be the distance between the skier home origin and the selected ski resort. Our initial purpose was to build the gravity model or the radiation model (Simini, et al., 2012) using this information. Even though the distance between resorts does not exactly represent the reality of the dynamic with the available data it was the only solution to include in this first version the distance effect on the decision process. To overcome this limitation, a future survey will gather information about the origin and travel behavior of skiers to consider skier home origin and not the frequented ski resort. Finally, the gravity approach, lacking a powerful theoretical guidance, relies on adjustable parameters to fit empirical data that vary from region to region. In this line, non-parametric approaches like the radiation model (Simini et al., 2012.) could be tested in a future in order to improve the projected redistribution of skiers among the remaining ski resorts.

6. CONLUSIONS

A georeferenced ABM methodology coupled with a gravity model was used to simulate climate change impacts on winter tourism, and specifically used to analyze the interaction between physical changes (i.e., snowpack and resulting season length) and socioeconomic implications (i.e., potential shifts in number of skiers). Unlike many of the models used to date to analyze climate change impacts on ski industry, this methodology permits the inclusion of behavioral response of skiers. The study assessed the effects of spatial and activity substitution on the shifts in the future redistribution of skiers among the ski resorts at a regional scale. This study proposes a new approach to better understand and explore how the potential behavioral responses identified in previous studies could affect the final outcome of climate change impacts assessment. In addition to the identified behaviors and responses of tourists, this framework could be also useful in a future to explore the influence of tourist behavior and responses to other factors that could affect their dynamics such as petrol price or crowding avoidance in destinations once the appropriate information have been generated and available.

Thus, this approach fosters the understanding of the climate change impacts on winter tourism in any region of the world, by means of a better characterization of the variability of the ski resorts vulnerability in a close geographical area including the effect of the behavioral adaptation of tourists. The high variability detected on the level of impacts at short distances leads not to a significant regional pattern about the vulnerability. In this line, we found that in the same region can be two resorts located at a really short distance with significant different level of vulnerability. However and congruent with previous cited literature, low elevation areas, with a predominance of south oriented slopes present a higher vulnerability. In the particular case of the Pyrenees, those resorts with a higher Mediterranean influence and those with little diversity of complementary activities to ski were identified as the more vulnerable to future climate change. Otherwise, those with a higher Atlantic influence, located at higher elevations, more north oriented and with a more diversified complementary to ski activities were identified as the more resilient ones. In the case of the Pyrenean region, our results show that, even more than a significant reduction in the ski market, the main effect of climate change will be a redistribution and consolidation of the current market, reallocating the visitors of more vulnerable ski resorts to the most resilient ones, able to offer longer ski seasons plus having a higher attractiveness factor than their competitors. Furthermore, the clustering of the ski resorts on the basis of their vulnerability is of a great value for managers and policymakers in order to identify targets to focus the efforts and design the suitable measures for adaptation strategies for each ski resort.

Acknowledgements

The authors are thankful to Dr. Ignacio López-Moreno for share and support in climate projections data and to the Working Community of the Pyrenees (CTP) research projects CTTP1/10 and CTTP1/12, financially supported by the Government of Andorra. First author acknowledges also a predoctoral grant from the Andorran Government [BTC2010/2013-0006-AND].

7. BIBLIOGRAPHY

Abegg, B. 1996. *Klimaänderung und Tourismus. Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. vdf Hochschuleverlag, Zurich.

Abegg B, Agrawala S, Crick F, de Montfalcon, A. 2007. *Climate change impacts and adaptation in winter tourism*. In: Climate change in the European Alps: adapting winter tourism and natural hazards management. Paris: Organization for Economic Co-operation and Development.

Alexandru, A., de Elía, R., Laprise, R. 2007. Internal variability in regional climate downscaling at the seasonal time scale. *Mon Weather Rev* 135(9), 3221–3238

Andorra Turisme. 2012. *National Tourism Surveys*. Andorra Government.

ATUDEM. 2013 *Dossier de premsa 2012-2013*. Associación Tursítica de Estaciones De Esquí y Montaña.

Axtell, R. L., Epstein, J. M., Dean, J. S., Gumerman, G. J., Swedlund, A. C., Harburger, J., Chakravarty, S., Hammond, R., Parker, J., Parker, M. 2002. Population Growth and Collapse in a Multi-Agent Model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences* 99(3), 7275-7279.

Baggio, R. 2008. *Symptoms of complexity in a tourism system.* Tourism Analysis 13,1-20

Balbi, S., Giupponi, C., Perez, P., Alberti, M. 2013. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environmental Modelling & Software*, 45,29 - 51

Bark, R., Colby, B., Dominguez, F. 2010. Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. *Climatic Change* 102, 467–491.

Becken, S. 2005. Harmonising climate change adaptation and mitigation: The case of tourist resorts in Fiji. *Global Environmental Change*, 15 (4), 381-393

Behringer, J., Bürki, R., Fuhrer, J. 2000. Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. *Integrated Assessment* 1(3), 331–338

Bithell, M., Brasington, J., 2009. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environmental Modelling & Software* 24 (2), 173–190.

Botti, L., Goncalves, O., Peypoch, N. 2013. Benchmarking Pyrenean ski resorts. *Journal of Alpine Research*, 100-4.

Crooks, A. T., 2010. Constructing and Implementing an Agent-Based Model of Residential Segregation through Vector GIS. *International Journal of Geographical Information Science,* 24(5), 661-675.

Dawson, J., 2009. Climate Change Vulnerability of the US Northeast Ski Sector: A multi-methods systems-based approach. Thesis (PhD) Department of Geography and Environmental Management, University of Waterloo.

Dawson, J., Scott, D., McBoyle, G. 2009. Climate change analogue analysis of ski tourism in the northeastern USA. *Clim Res* 39,1–9

Dawson, J., Havitz, M., Scott, D., 2011. Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty. *Journal of Travel & Tourism Marketing*, 28 (4), 388-404.

Dawson, J., Scott, D. (2012) Managing for Climate Change in the Alpine Ski Sector. *Tourism Management*. 35, 244-254.

Dawson, J., Scott, D., Havitz, M. 2013. Skier demand and behavioural adaptation to climate change in the US Northeast. *Leisure/ Loisir*, 37(2), 127-143.

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

Ford, J.D., Keskitalo, E.C.h:, Smith, T., Pearce, T., Berrang-Ford, L., Duerden., F. and Smit, B. 2010. Case study and analogue methodologies in climate change vulnerability research. *WIRE's Climate Change*, 1(3):374-392.

Fukushima, T., Kureha, M., Ozaki, N., Fujimori, Y., Harasawa, H., 2002. Influences of air temperature change on leisure industries: case study on ski activities. *Mitigation and Strategies for Climate Change 7:173-189.*

Gimblett, R., Skov-Petersen, H., 2008. *Monitoring, Simulation, and Management of Visitor Landscapes*. University of Arizona, Tuscon.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, Grand, T., Heinz, S. K., and Huse, G. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198(1-2), 115-126.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F. 2010. The ODD protocol for describing individual-based and agent-based models: A first update. *Ecological Modelling*, 221, 2760-2768.

Gössling, S., D. Scott, C., Michael Hall, J.-P. Ceron and Dubois, G. 2012. Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, 39(1), 36-58.

Hamilton, L, Brown, C., & Keim, B. D. 2007. Ski areas, weather and climate: Time series models for New England case studies. *International Journal of Climatology*, 27, 2213–2124.

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, Australia

Isard, W. 1960. *Methods of regional analysis: an introduction to regional science*. The MIT Press, Cambridge.

Hoffmann, V H; Sprengel, D C; Ziegler, A; Kolb, M; Abegg, B. 2009. Determinants of corporate adaptation to climate change in winter tourism: an econometric analysis. *Global Environmental Change*, 19(2), 256 -264.

IPCC. 2007. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom & New York, NY, USA: Cambridge University Press.

Itami, R., Raulings, R., MacLaren, G., Hirst, K., Gimblett, R., Zanon, D., Chladek, P. 2002. RBSim 2: Simulating the complex interactions between human movement and the outdoor recreation environment. In *Monitoring and Management of Visitor Flows in Recreational and Protected Areas.* Conference Proceedings, A. Arnberger, C. Brandenburg, A. Muhar, Institute for Landscape Architecture and Landscape Management University of Agricultural Sciences, Vienna, Austria, 30 Jan – 02 Feb 2002 pp 191-198.

Janssen, M. A. 2009. Understanding artificial anasazi. *Journal of Artificial Societies and Social Simulation*, 12.

Johnson, P. A., Sieber, R. E. 2009. Agent-based modelling: A dynamic scenario planning approach to tourism PSS. In S. Geertman & J. Stillwell (Eds.), *Planning Support Systems: Best Practices and New Methods* (pp. 211-226). Berlin: Springer.

Johnson, P. A., Sieber, R. E. 2010. An Individual-Based Approach to Modeling Tourism Dynamics. *Tourism Analysis*, 15(5),517-530.

Johnson, P. A., Sieber, R. E. 2011. An Agent-Based Approach to Providing Tourism Planning

Support. *Environment and Planning B - Planning and Design*, 38(3), 486-504.

Jung, W. S., Wang, F., Stanley, H. E. 2008. Gravity model in the Korean highway. *EPL* 81, 48005.

Kaluza, P., Kölzsch, A., Gastner, M. T., Blasius, B. 2010. The complex network of global cargo ship movements. *J. R. Soc. Interf.* 7, 1093–1103.

Karemera, D., Oguledo, V.I., Davis, B. 2000. A gravity model analysis of international migration to NorthAmerica. *Appl Econ* 32(13), 1745-1755.

Kohler, T. A., Gumerman, G. J. 1999. *Dynamics in human and primate societies: Agent-based modeling of social and spatial processes*. New York: Oxford University Press.

Krings, G., Calabrese, F., Ratti, C., Blondel, V. D. 2009. Urban gravity: a model for intercity telecommunication flows. *J. Stat. Mech*, L07003.

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

Ligmann-Zielinska, A., Jankowski, P. 2007. Agent-based models as laboratories for spatially explicit planning policies. *Environment and Planning B,* 34,316-335

March, H., Saurí, D., Llurdés, J.C. 2014. Perceptions on the effects of climate change in winter and summer tourists areas: The Pyrenees and the Catalan and Balearic coasts, Spain. *Regional Environmental Change*, 14(3), 1189-1201.

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

Manson, S. M., Evans, T. 2007. Agent-based modeling of deforestation in southern yucatán, mexico, and reforestation in the midwest united states. *Proceedings of the National Academy of Sciences*, 104(52), 20678-20683.

Moen, J., Fredman, P. 2007. Effects of climate change on alpine skiing in Sweden. *Journal of sustainable tourism* 15: 418-437.

Monge, G. 1781. *Mémoire sur la Théorie des Déblais et de Remblais.* Histoire de l'Académie Royale des Sciences de Paris, avec les Mémoires de Mathématique et de Physique pour la même année 666–704 (De l'Imprimerie Royale, 1781).

Parker, D.C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. *Annals of the Association of American Geographers* 93(2), 314-337.

Perez, L., Dragicevic, S. 2010. *Environmental Modelling & Software* 25 (2), 223-236

Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover, È. 2012. Modeling climate change effects on winter ski tourism in Andorra. *Clim Res* 54, 197-207

Pöyhönen, P. 1963. *A tentative model for the volume of trade between countries.* Weltwirtschaftliches Arch. 90, 93–100.

Pütz, M., Gallati, D., Kytzia, S., Elsasser, H. and others 2011. Winter tourism, climate change, and snowmaking in the Swiss Alps: tourists' attitudes and regional economic impacts. *Mt Res Dev* 28, 292−298

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. *Journal of Sustainable Tourism*, 14(4), 376–398

Scott, D., Dawson, J., Jones, B. 2008. Climate change vulnerability of the US northeast winter recreation– tourism sector. *Mitigation and Adaptation Strategies for Global Change* 13 (5), 577-596.

Scott, D., Gössling, S., Hall, C.M. 2012, *Climate Change and Tourism: Impacts*, Adaptation and Mitigation. London: Routledge. 423 pgs.

Simini, F., González, M., Maritan, A., Barabási, A.-L., 2012. A universal model for mobility and migration patterns. *Nature,* 484, 96-100.

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

Smajgl, A., Heckbert, S., Ward, J., Straton, A., 2009. Simulating impacts of water trading in an institutional perspective. *Environmental Modelling & Software* 24(2), 191–201.

Steiger, R. 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Clim Res* 43, 251−262

Steiger, R. (2011). The impact of snow scarcity on tourism. An analysis if the record warm seson 2006/2007 in Tyrol (Austria). *Tourism Review* 66(3):4-13

Steiger R, Abegg B. 2013. The sensitivity of Austrian Ski areas to climate change. *Tourism, planning and development*, 480-493.

Thiemann, C., Theis, F., Grady, D., Brune, R. & Brockmann, D. 2010. The structure of borders in a small world. *PLoS ONE* 5, e15422.

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. *International Journal of Climatology* 29, 1048–1055

Unbehaun, W., Probstl, U., & Haider, W. 2008. Trends in winter sports tourism: Challenges for the future. *Tourism Review*, 63(1), 36–47.

Viaggi, D., Bartolini, F., Raggi, M. 2009. Combining linear programming and principal–agent models: an example from environmental regulation in agriculture. *Environmental Modelling & Software* 24 (6), 703–710.

Zipf, G. K. 1946. The P1P2/D hypothesis: on the intercity movement of persons. Am. *Sociol. Rev.* 11, 677–686.

Influencia del cambio climático en el turismo de nieve del Pirineo. Experiencia del proyecto de investigación NIVOPYR

Marc Pons [a,b], Juan Ignacio López Moreno[c] Pere Esteban[d], Santi Macià[d], Jordi Gavaldà[e], Carles García[f], , Martí Rosas[b] y Eric Jover[a]

a Observatori de la Sostenibilitat d'Andorra (OBSA)
b Sustainability Measurement and Modeling Laboratory de la Universitat Politècnica de Catalunya (SUMMLAB-UPC)
c Instituto Pirenaico de Ecología del Consejo Superior de Investigaciones Científicas (IPE-CSIC)
d Centre d'Estudis de la Neu i la Muntanya d'Andorra del Institut d'Estudis Andorrans (CENMA-IEA)
e Centre de Lauegi d'Aran, Conselh Generau d'Aran
f Institut Geològic de Catalunya (IGC)

(Accepted in *Pirineos* in June 2014)

Abstract:

In the last decades, several studies have demonstrated and given a valuable insight about the existence of a global climate change. Even though the existence of a high regional heterogeneity about the level and temporality of climate change impacts, the trends of the potential future changes on the temperature and precipitation patterns are better known and consequently the potential impacts on the biosphere and the cryosphere. In this context, mountain regions have been identified as highly vulnerable areas to the effects of climate change and especially interesting areas for the detection and assessment of the potential changes and impacts. Moreover, in the last few decades, winter tourism, highly dependent on weather and snow availability, has become one of the main economic activities and source of local development in many mountain regions around the world. The Pyrenees, one of the most important winter tourism areas in Europe after the Alps, is a clear example of this pattern.

The aim of the NIVOPYR project, an international research project in the framework of the Working Community of the Pyrenees (CTP), is to analyze the effects of the climate change on the winter tourism, and especially alpine ski tourism, in the Pyrenees. In order to achieve this objective the project intended to joint the current knowledge about the effects of climate change on temperatures, precipitations, snow cover and skiers behavior in the Pyrenees and develop for first time objective and accurate results for this area. To achieve this goal several methods have been used including, historical analysis of climatical series evolution, assessment of different future climate change scenarios for the Pyrenees, modeling future snowpack based on surface energy balance models and agent based modeling for coupling physical and socioeconomic parameters. One of the main results of this project was the identification of different ski resorts profiles depending on their vulnerability to climate change. Three different groups were identified. The first group includes the high vulnerable ski resorts, effected both by a mid and a high-climate change scenario. The second group, includes the low vulnerable ski resorts, affected by a high-climate change scenario but able to be viable with technical adaptation measures in a mid-climate change scenario. Finally, the group of resilient ski resorts includes the geographically and socioeconomically privileged compared to the rest of Pyrenean ski resorts. These ski resorts would be viable both in a mid and a high-climate change scenario just applying technical adaptation strategies.

Keywords: Climate Change, Snow Cover, Winter tourism, Pyrenees, Adaptation Climate uncertainty.

Resumen:

En los últimos años multitud de estudios han evidenciado y corroborado la existencia de un cambio climático global. A pesar de la existencia de una gran heterogeneidad regional en el grado y la temporalidad de los posibles impactos del cambio climático, cada vez se conocen mejor cuales pueden ser las tendencias futuras sobre posibles cambios en regímenes de temperatura y precipitaciones y por lo tanto en otros impactos indirectos sobre la biosfera o la criosfera. En este contexto, las áreas de montaña han sido identificadas como regiones especialmente vulnerables a los efectos del cambio climático y zonas de gran interés para la detección y evaluación de los posibles impactos. Por otro lado, en las últimas décadas, el turismo de invierno, altamente sensible a los cambios en la meteorología y la disponibilidad de nieve, se ha convertido en una de las principales actividades económicas en muchas zonas de montaña y ha jugado un papel clave y fundamental como fuente de ingreso y desarrollo local. Un claro ejemplo es el caso de los Pirineos, una de las regiones europeas más importantes en lo que se refiere a turismo de invierno después de los Alpes.

La motivación principal del proyecto NIVOPYR, proyecto de investigación multinacional en el marco de la Comunidad de Trabajo de los Pirineos (CTP), es la de evaluar la posible influencia del cambio climático en la evolución del turismo de nieve, y más específicamente el esquí alpino, en esta región. Así, se han realizado diferentes tareas orientadas a integrar el conocimiento ya existente en los patrones presentes y futuros de las temperaturas, precipitaciones, cobertura de nieve y comportamiento de los esquiadores, desarrollar metodologías de análisis y obtener por primera vez datos objetivos para la región Pirenaica. De este modo, se han obtenido tres perfiles diferentes de estaciones de esquí dependiendo de su vulnerabilidad frente al cambio climático. Un primer grupo de estaciones, identificado como altamente vulnerables, se vería afectado tanto por un escenario de cambio climático medio como en uno de mas intensivo y por lo tanto deberán contemplar la aplicación de medidas de adaptación estructurales, como una mayor desestacionalización y diversificación de su actividad turística. Las estaciones del segundo grupo, consideradas de baja vulnerabilidad, podrían seguir operando con medidas de adaptación técnicas bajo un escenario de cambio climático medio pero no bajo un escenario de cambio climático más intenso. Finalmente, el tercer grupo, engloba las estaciones consideradas como resilientes. Estas estaciones, debido a una situación geográfica y socioeconómica privilegiada frente al resto de estaciones del Pirineo, se verían poco afectadas tanto por un escenario medio de cambio climático como uno de más elevado.

Palabras clave: Cambio climático, Cobertura de nieve, Turismo de invierno, Pirineos, Adaptación, Variabilidad Climática.

1. Introducción

En las últimas décadas, el turismo de invierno y de nieve se ha convertido en una de las principales actividades económicas en muchas zonas de montaña y ha jugado un papel clave y fundamental como fuente de ingreso y desarrollo local (WTO-UNEP, 2003; Lasanta et al., 2007). Se estima que el turismo de invierno, principalmente el generado por las estaciones de esquí alpino, mueve anualmente unos 400 millones de visitantes en las principales cordilleras del mundo (Vanat, 2013). Un claro ejemplo es el caso de los Pirineos, una de las regiones europeas más importantes en lo que se refiere a turismo de invierno después de los Alpes. Con unos 11 millones de visitantes al año repartidos en las más de 50 estaciones de esquí de fondo y alpino españolas, francesas y andorranas, el sector del turismo de nieve, ya sea de forma directa o indirecta, actúa como principal actividad económica y de desarrollo para gran parte de las comarcas y regiones pirenaicas que en gran medida se sustentan y dependen de este sector[1]. En el caso del Pirineo, el impacto socioeconómico de las estaciones de esquí ha sido desigual, a la vez que ha conllevado unos impactos ambientales asociados al abandono del sector primario y una transición hacia una económica fuertemente dependiente del turismo de esquí principalmente en las proximidades de las estaciones (Lasanta et al., 2007b).

Por otro lado, en los últimos años multitud de estudios han evidenciado y corroborado la existencia de un cambio climático global (IPCC, 2013). A pesar de la existencia de una gran heterogeneidad regional en el grado y la temporalidad de los posibles impactos del cambio climático, cada vez se conocen mejor cuales pueden ser los posibles cambios en regímenes de temperatura y precipitaciones y por lo tanto en otros impactos indirectos, como la biosfera o la criosfera. En este contexto, las zonas de montaña han sido identificadas como regiones especialmente vulnerables a los efectos del cambio climático (Beniston, 2003). Por un lado, debido al ritmo al que se están produciendo estos cambios, por ejemplo en el incremento de la temperatura media terrestre, el cual se está detectando ser superior a la media global (El Kenawy, 2012; Esteban et al. 2012). Por otro lado, el gradiente altitudinal propio de los territorios de montaña induce a una gran variedad fisiológica y biológica con abruptos cambios en la fauna y la vegetación y

---

[1] Datos propios obtenidos a partir de hemeroteca , DSF, 2012, ATUDEM, 2013 y SkiAndorra 2013 .

con una gran sensibilidad a pequeñas variaciones climáticas (Keller, 2000). Finalmente, el fuerte vínculo existente entre sistemas naturales y sociales en las zonas de montaña conlleva que el impacto de los cambios ambientales sea mucho más evidente y directo que en otras zonas. Cambios en los regímenes de precipitaciones y por lo tanto en los patrones hidrológicos pueden alterar la capacidad de producción hidroeléctrica o cambios en la ocurrencia de fenómenos extremos pueden inducir un incremento de los impactos socioeconómicos derivados de los riesgos naturales como los aludes o los deslizamientos. Sin embargo, uno de los ejemplos más evidentes es la vulnerabilidad del turismo de nieve frente a los posibles efectos del cambio climático. A pesar de que el cambio climático es sólo uno de los factores que influyen en el turismo de invierno, la presencia o ausencia de nieve, en concreto el espesor de nieve y su temporalidad son elementos claves a la hora de valorar la viabilidad y la sostenibilidad a medio y largo plazo del sector. Por este motivo, la evaluación de los efectos del cambio climático sobre la cobertura natural y la capacidad de producción de nieve es vital y necesaria para valorar los posibles impactos socioeconómicos en una región tan dependiente de esta actividad como los Pirineos.

Hasta la fecha, diversos estudios han analizado con mayor o menor detalle la afectación del cambio climático en algunas de las principales regiones alpinas del mundo. La mayoría de estos estudios se han centrado en los Alpes (König & Abegg, 1997; Breiling & Charamza, 1999; Elsasser & Bürki, 2002; Abegg et al, 2007; Steiger, 2012; Steiger et al, 2013; Uhlmann et al., 2009; Töglhofer et al., 2011), Canadá (McBoyle& Wall, 1987; Scott et al., 2003; 2007) y los Estados Unidos (Dawson et al., 2010; 2013), aunque países como Suecia (Moen& Fredman, 2007), Australia (Hennessy et al., 2003; Bicknell&McManus, 2006), Japón (Fukushima et al., 2003) o Nueva Zelanda (Hendrikx&Hreinsson, 2012) también han sido analizados. Sin embargo, en el momento de iniciar este proyecto, no existía ningún estudio científico que analizara la influencia del cambio climático en el turismo de invierno en los Pirineos.

Algunos de estos estudios, principalmente enfocados en analizar los impactos en la oferta (estaciones de esquí), solo tienen en cuenta la nieve natural en sus modelos (Uhlmann et al., 2009) o utilizan indicadores que no son relevantes para las estaciones de esquí como por ejemplo los días de cobertura de nieve, definidos con un umbral de 2,5 cm de nieve (Lamothe & Périard, 1988), cuando las estaciones de esquí requieren espesores de entre 20-100 cm de nieve para operar una pista de esquí (Scott et al, 2012). Con la excepción de algún estudio utilizando modelos estadísticos relacionando el espesor de nieve con otros parámetros climatológicos, (Moen and Fredmand, 2007), la mayoría utilizan modelos físicos de nieve. Una de las mayores limitaciones del uso de modelos estadísticos es que omiten el efecto de los sistemas de producción de nieve en la disponibilidad de nieve. Esta limitación, no solo presente en los estudios con modelos estadísticos, sino también en algunos usando modelos físicos es la principal limitación de la mayoría de estudios analizando la vulnerabilidad de las estaciones de esquí (Scott et al., 2012). Este aspecto, es clave ya que los estudios omitiendo los efectos, tanto positivos como negativos de la nieve de producción no permiten reflejar la realidad de la situación en la mayoría de estaciones de todo el mundo. En la actualidad, gran parte de los dominios esquiables están equipados con sistemas de producción de nieve y el porcentaje de pistas cubiertas se ve incrementado año a año (Steiger, 2008). Los estudios incorporando este aspecto (Scott et al., 2003, 2007; Hennessy et al., 2008; Steiger, 2010) muestran en diferentes regiones que el impacto previsto en estudios previos, teniendo en cuenta solo la nieve natural, sería en realidad menor cuando se tiene en consideración este aspecto. A pesar de estas limitaciones y la heterogeneidad de metodologías utilizadas, la mayoría de estos estudios son congruentes en señalar que un futuro cambio climático podría conllevar un impacto negativo en la duración de las temporadas de esquí, la reducción de zonas esquiables y una disminución del número de esquiadores tanto en estaciones de baja altitud como de baja latitud.

En este contexto, la motivación principal del proyecto NIVOPYR, proyecto de investigación multinacional en el marco de la Comunidad de Trabajo de los Pirineos (CTP), es la de evaluar la posible influencia del cambio climático en la evolución del turismo de nieve en esta región. El proyecto se ha centrado en el esquí alpino debido a que es el que genera un mayor impacto socioeconómico. Así se han realizado diferentes tareas orientadas a integrar el conocimiento ya existente, desarrollar metodologías de análisis y obtener nuevos datos necesarios para responder a este objetivo.

La primera tarea era poner en común el conocimiento y el trabajo que en los últimos años diferentes instituciones de investigación han desarrollado en lo que se refiere al estudio del clima en los Pirineos, y en especial, lo referente a la variabilidad y disponibilidad de la nieve y sus repercusiones ambientales y socioeconómicas. Por un lado, el proyecto ha permitido recopilar e integrar los registros históricos de las estaciones disponibles en los Pirineos. Por otro lado, se han calculado indicadores climáticos y nivológicos para diferentes regiones del Pirineo y se han aplicado metodologías como el análisis de imágenes satélite, para ayudar a la comprensión, gracias a su evolución temporal, tanto de la variabilidad climática natural como de la influencia del cambio climático, haciendo un especial énfasis en la evolución del manto nivoso. Este conjunto de datos permite una mejor comprensión de las diferencias en los cambios que se están produciendo en los Pirineos respecto a otras regiones de montaña así como la variabilidad dentro de la misma cordillera pirenaica.

En una segunda fase, se han recopilado todos los datos referentes a escenarios de cambio climático a partir de los modelos regionales disponibles para los Pirineos. A partir de sus proyecciones se ha realizado una detallada clasificación comparativa de variables físicas como las temperaturas, precipitaciones o espesores de nieve en función de los diferentes escenarios de emisiones y el horizonte temporal de las proyecciones. Con el fin de entender mejor la variabilidad futura del manto nivoso en los Pirineos, en esta segunda fase del proyecto se ha realizado una síntesis general de cómo el cambio climático puede afectar concretamente al manto de nieve del Pirineo. Además, se han realizado simulaciones del balance de energía bajo condiciones observadas y distintos escenarios de cambio climático mediante análisis de sensibilidad o utilizando proyecciones de modelos climáticos regionales (RCM's).

Finalmente, se han vinculado los cambios físicos sobre el manto de nieve con la vulnerabilidad futura de las estaciones de esquí. Una de las grandes carencias en la comprensión de los posibles impactos del cambio climático a nivel socioeconómico ha sido la falta de herramientas que permitan proyectar de forma objetiva las posibles repercusiones tanto sociales como económicas de los impactos físicos del cambio climático. De este modo, el objetivo final del proyecto ha sido el de comprender mejor y vincular de forma objetiva los posibles cambios sobre el manto de nieve y las capacidades futuras de producción de nieve con la vulnerabilidad resultante de las estaciones de esquí de los Pirineos. Esta fase ha permitido crear una herramienta de ayuda a la planificación y toma de decisiones en dominios esquiables tanto para las administraciones públicas como para las empresas privadas del sector.

2. Estructura del proyecto

Este trabajo es el resultado de un proyecto de investigación de la CTP y más específicamente de su convocatoria del 2010 (desarrollo del proyecto durante los años 2011 y 2012). Las regiones y países incluidos en este proyecto fueron Andorra, España (Aragón y Cataluña) y Francia. Más concretamente el ámbito geográfico del proyecto incluye las 49 estaciones de esquí alpino más importantes del Pirineo concentradas en una franja central limitada al oeste por La Pierre Saint-Martin y al este por Vallter 2000.
Una de las peculiaridades de este proyecto es que integró tipologías muy variadas de actores. De hecho se organizaron los participantes en tres grupos de trabajo:

- El grupo físico aglutinaba a los climatólogos y debía aportar datos relacionados tanto con la variabilidad histórica de parámetros climáticos en los Pirineos como la posible influencia del cambio climático en estas variables.
- El grupo técnico, formado por profesionales de la nieve, tenía como objetivo facilitar los datos socioeconómicos relacionados con el turismo de nieve al resto de participantes, tales como la frecuentación de esquiadores o los días de apertura, así como identificar las variables técnicas que condicionan la viabilidad de las estaciones de esquí, por ejemplo el mínimo de espesor requerido para operar una pista de esquí.
- El grupo de modelización tenía por objetivo correlacionar los datos provenientes tanto del grupo físico como del grupo técnico. Para este fin se han utilizado diferentes metodologías como la estadística inferencial, la dinámica de sistemas y la modelización conjunta de modelos por agentes integrados en Sistemas de Información Geográfica.

La estructura de este proyecto fue concebida con el objetivo de maximizar el realismo y la aplicabilidad de los modelos desarrollados. En la Figura 1 se puede observar el mapa conceptual del trabajo dónde se identifican dos grupos de variables. La primera parte del modelo, tiene por objetivo evaluar el espesor de nieve a diferentes cotas altitudinales y diferentes zonas de los Pirineos con el objetivo de identificar las zonas que permiten garantizar los 30 cm de nieve que es uno de los criterios internacionalmente reconocidos de viabilidad de una estación de esquí (Witmer, 1986). En este sentido, no sólo se ha considerado la nieve natural sino también la potencialidad de producción de nieve de cultivo. La segunda parte del modelo incluye tanto las variables socioeconómicas relacionadas con la actividad del esquí como la respuesta adaptativa de los esquiadores al cambio climático.

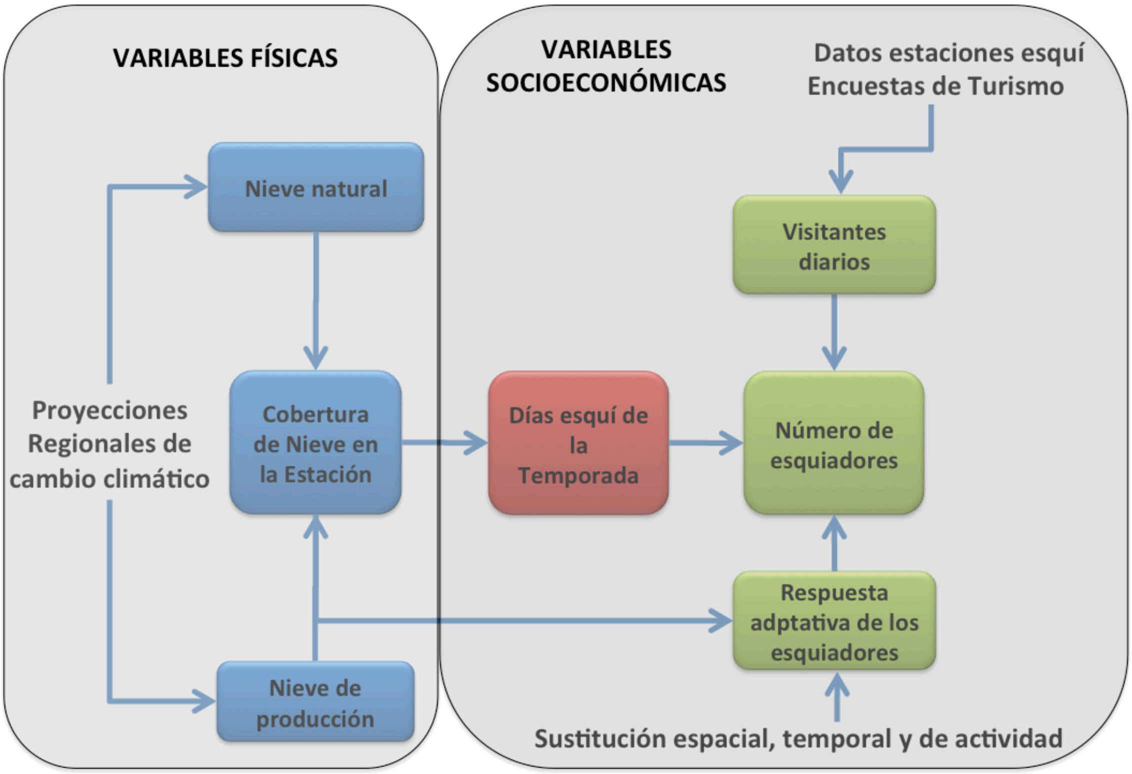


Figura 1. Diagrama del proyecto y del modelo desarrollado.

3. Resultados

3.1 Ejemplo de reconstrucción histórica

En cualquier estudio de cambio climático es imprescindible tener un buen conocimiento de la evolución histórica del clima. Esto puede ser una dificultad si hacemos referencia a zonas de alta montaña del Pirineo dónde escasean las series de datos y en mayor medida los datos de calidad. En el marco de este proyecto, se ha aprovechado para revisar y corregir varias series de alta montaña del Pirineo Catalán. También se ha creado una serie única a partir de los datos de La Molina y de Vall de Núria con la finalidad de tener una serie continua entre los años 1955 y 2012. Otra forma de estudiar la evolución del clima es a través de indicadores climáticos de referencia. Este tipo de datos ayudan a identificar las evidencias del cambio climático. Algunos de los resultados obtenidos en el marco de este proyecto ya han sido publicados en esta misma revista (Esteban et al. 2012).

3.2 Recopilación de escenarios existentes

El conocimiento de las tendencias históricas de la evolución climática del Pirineo genera datos muy relevantes. Sin embargo, en el marco de este proyecto era necesario evaluar también sus posibles evoluciones futuras. Cada modelo climático se basa en unas hipótesis y metodologías de trabajo que lo hacen único. En este sentido, es interesante usar diversos modelos sumando así sus diferentes perspectivas y abordar de la manera más sólida posible el reto de la incertidumbre. Con este objetivo se han analizado los diferentes modelos de cambio climático existentes para el Pirineo considerando tanto modelos dinámicos como proyecciones estadísticas derivadas. En este sentido se han usado los modelos siguientes:

- Información facilitada por MeteoFrance, proyecto ANR/SCAMPEI. A partir de las modelizaciones a escala global ARPEGE y LMDZ (resoluciones entre 50 y 300 km) se ha pasado a modelos mesoescalares como el ALADIN, el MAR y una versión especial del LMDZ. Además se hicieron correcciones estadísticas de las salidas basándose en análogos gracias a los datos de la red SAFRAN. A partir de aquí se obtienen los resultados para diferentes escenarios de cambio climático y para diferentes horizontes temporales y con una resolución de 8 km. En este trabajo se han analizado los resultados para 30 puntos distribuidos por todo el Pirineo francés (SCAMPEI, 2012).

- Información obtenida a partir de la Agencia Estatal de Meteorología (AEMET) – Generación de escenarios regionalizados de cambio climático para España. De la información disponible se ha trabajado con los resultados derivados de dos proyecciones del CMIP3-AR4 IPCC (la del modelo canadiense CCCMA_CGM3_1 y el modelo alemán MPI_ECHAM5) y tres del proyecto ENSEMBLES (modelo alemán MPEH5, el noruego BCCR_BCM2 y el francés CNR-CM3). De estas proyecciones se obtienen diferentes escenarios de cambio climático para 19 puntos del Pirineo español por lo que hace referencia a las temperaturas (mínimas y máximas) y 60 puntos para datos de precipitación. (Brunet et al., 2009)

- Información obtenida a partir del Servei Meteorològic de Catalunya (SMC) – proyecto ESCAT (Barrera-Escoda y Cunillera, 2011; ESCAT, 2012). A partir de las salidas de modelos globales (el alemán ECHAM5), se deriva información de alta resolución a partir del acoplamiento de modelos meteorológicos mesoescalares (MM5) con los de circulación general y así derivar la información a gran escala hasta los 15 km de resolución. En este trabajo se han considerado valores globales para el Pirineo catalán de temperatura, precipitación, viento y humedad relativa para diferentes escenarios de cambio climático.

Sumando estas diferentes fuentes de información se puede obtener una buena perspectiva de las posibles tendencias de las alteraciones provocadas por el cambio climático en la temperatura y las precipitaciones para el conjunto del Pirineo y considerando una importante variabilidad metodológica. Centrándonos en la temporada invernal y, como ejemplo, presentamos en la siguiente figura la evolución de la temperatura máxima para tres horizontes temporales cercano (2020-2050), mediano (2040-2070) y lejano (2070-2100) y para diferentes escenarios de cambio climático (A1B, A1B-1, A1B-2, A2 y B1) (Figura 2). La temperatura máxima muestra un importante impacto de las concentraciones de gases de efecto invernadero futuras con incrementos en todos los puntos y escenarios estudiados. Este incremento medio es más marcado cuanto más lejano es el horizonte temporal pasando de entre 1,1° y 1,9°C para el horizonte cercano a entre 2,1° y 4°C para el horizonte lejano. También cabe destacar que cuanto más lejana es la proyección mayor es la variabilidad de los resultados tanto de un mismo modelo en diferentes zonas geográficas como entre diferentes modelos. En definitiva, hay un incremento de la incertidumbre y de la disparidad de los resultados. Así por ejemplo, para el horizonte lejano algún modelo (BCCR_BCM3) muestra sólo incrementos moderados e incluso en algunos puntos inferiores a +1°C cuando el modelo LMDZ muestra resultados que en algunos casos pueden superar los +5°C.

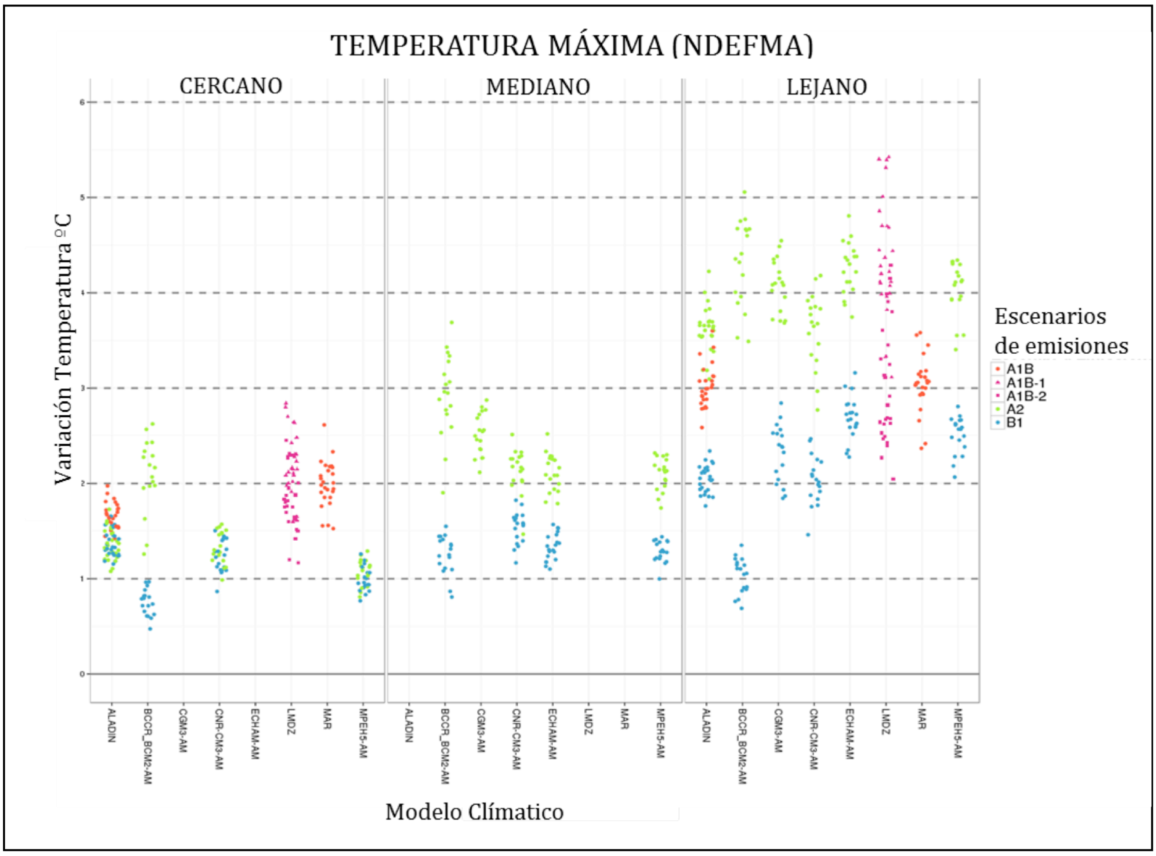


Figura 2. Distribución de la evolución de la temperatura máxima (de noviembre a abril) invernal de diferentes puntos del Pirineo en función de diferentes modelos, escenarios de emisiones y a diferentes horizontes temporales. Para abordar el

problema de la incertidumbre se han utilizado diferentes modelos de diferentes fuentes: Météo-France (SCAMPEI) i AEMET.

3.3 Escenarios específicos de evolución del manto de nieve

Uno de los objetivos del proyecto era poder determinar qué evolución podría tener el manto de nieve en diferentes zonas del Pirineo y para diferentes bandas altitudinales. Con este objetivo se realizaron diferentes proyecciones que sirvieron como datos de entrada al modelo regional detallado en la siguiente sección. Así por ejemplo se han usado por un lado, resultados ya publicados sobre proyecciones del manto nivoso en el Pirineo, generados a partir de un modelo de balance de energía de la nieve alimentado por proyecciones futuras, a partir del modelo climático regional HIRHAM (Christensen et al., 1998), de las variables: temperatura del aire, punto de rocío, precipitación, viento, presión en superficie y radiación solar incidente (López-Moreno et al., 2009). Por otro lado, también se han generado datos nuevos obtenidos a partir de la modelización del manto de nieve a 2000 m de altura en una estación meteorológica cercana a la estación de esquí de Formigal (Izas a 2.056 m). Para ello, se ha utilizado el modelo CRHM (Cold Region Hydrological Model). Los resultados han mostrado cómo bajo los escenarios de cambio climático podemos tener una reducción de entre el 15 y 25% de acumulación de nieve y entre el 10 y 20% de su duración (alrededor de un mes). El ritmo de fusión puede verse también notablemente alterado. Con el objetivo de adaptarse a las necesidades de datos físicos como entradas del modelo se han considerado dos escenarios de cambio climático. El primero correspondiendo a un incremento de +2°C, equivalente al escenario B2 del SRES IPCC (IPCC, 2007) y un segundo escenario más extremo con un incremento de +4°C, equivalente al escenario A2. El uso de la nomenclatura +2°C y +4°C para los escenarios se debe principalmente a dos motivos. Por un lado, la referencia solo al cambio de temperatura se debe a que el modelo HIRHAM predice que los cambios más importantes en la cobertura de nieve son causados en mayor medida por temperaturas más elevadas que por cambios en los patrones de precipitaciones. Por otro lado, para evitar hablar de escenarios SRES A2 y B2, con un horizonte temporal 2070-2100, se creyó conveniente simplificarlo con escenarios equivalentes +2, +4 grados para simplificar la comunicación hacia las administraciones y gestores de la estaciones de esquí. De este modo, el uso de esta nomenclatura permite equiparar los escenarios futuros a temporadas pasadas con una anomalía climática similar a la proyectada y analizar y concienciar a los actores implicados de los posibles impactos sobre el sector.

3.4 Modelo agregado de impactos físicos y socioeconómicos del cambio climático

Una vez analizados cuáles podrían ser los impactos del cambio climático a nivel físico y en especial, los efectos sobre la cobertura de la nieve del Pirineo, el siguiente paso ha sido el desarrollo de un modelo integral a escala regional que permita vincular estos posibles cambios físicos con las repercusiones socioeconómicas que supondrían sobre el turismo de invierno a nivel local y regional (Figura 1). Para este fin se ha creado un modelo georeferenciado basado en agentes (GIS+ABM) acoplado a un modelo gravitacional. El modelo basado en agentes (ABM) permite simular por un lado, la variación diaria de la cobertura de nieve a nivel local en cada una de las estaciones, y por lo tanto la capacidad de operar o no de dicha estación. De este modo, utilizando las proyecciones de nieve natural de modelos climáticos regionales, se simula diariamente, añadiendo la capacidad de producción de nieve, las condiciones diarias de cada estación para poder operar o no a lo largo de una temporada. Por otro lado, el modelo por agentes permite simular la respuesta adaptativa individual de los esquiadores en función de las condiciones de nieve de las estaciones, como por ejemplo, dejar de esquiar o ir hacia la estación más próxima con nieve disponible. Finalmente, el modelo gravitacional permite en función de la capacidad de atracción de las estaciones de esquí, basada en características tanto físicas (altitud, superficies esquiable,…) como comerciales (precio del forfait, actividades turísticas complementarias,…) y de la distancia entre estaciones, simular la redistribución potencial de esquiadores entre aquellas estaciones que siguen operando. Para analizar los efectos del cambio climático sobre el turismo de nieve del Pirineo, se han aplicado a dicho modelo integral cuatro escenarios diferentes. Un primer escenario, asume un incremento de la temperatura media invernal de 2°C. En un segundo escenario más intensivo de cambio climático, se asume un incremento de 4°C. Estos dos escenarios, solo contemplan la cobertura natural de nieve para determinar la capacidad de operar de las estaciones de esquí y nos permiten evaluar la vulnerabilidad natural de cada una de ellas. Para poder analizar la capacidad de la nieve de producción como medida de adaptación al cambio climático y realizar escenarios de futuro más realistas, ya que a día de hoy gran parte de los dominios esquiables ya disponen de estos sistemas de innivación, se ha incluido el efecto de esta tecnología en los otros dos escenarios. De este modo, se han simulado los efectos bajo un incremento de 2°C y 4°C teniendo en cuenta la capacidad de producir nieve en estos escenarios climáticos.

3.4.1 Vulnerabilidad natural y técnica de las estaciones de esquí del Pirineo.

El presente modelo se desarrolló primero a escala local para Andorra (Pons-Pons et al., 2012). El objetivo era probar el buen funcionamiento del modelo en un espacio limitado. Pero estos resultados tienen que considerarse como parciales ya que existe una importante interacción entre las estaciones (competencia) que sólo se tiene en consideración en un estudio más extenso de ámbito regional. A escala del Pirineo, el primer resultado que se obtiene del modelo integral es el análisis de la vulnerabilidad tanto natural como técnica de las estaciones de esquí de los Pirineos. Para determinar si una estación de esquí es o no viable, se ha utilizado el criterio a día de hoy más extendido en este tipo de análisis: la regla de los 30 cm durante 100 días (Abegg et al., 2007; Scott et al., 2003; Steiger 2010; Witmer, 1986). Según este criterio, se considera que una estación de esquí es viable cuando dispone de una cobertura de nieve de al menos 30 centímetros de nieve durante un mínimo de 100 días por temporada. De este modo, a partir de las proyecciones de cambios en la cobertura de nieve, se ha calculado la cantidad de estaciones viables de forma natural en una temporada promedio presente y bajo dos escenarios de cambio climático (+2°C y +4°C). Para las proyecciones de nieve natural, se han utilizado los resultados de López-Moreno et al, (2009), construidas a partir del modelo GRENBLS (Keller et al., 2005) utilizando como input variables climáticas

obtenidas a partir del modelo climático Regional HIRHAM (Christensen et al., 1998). Antes de realizar el análisis se ha realizado un downscaling espacial de las variables climáticas a cuatro bandas altitudinales: 1500, 2000, 2500 y 3000 metros. Las proyecciones de los cambios en la cobertura de nieve en el Pirineo se han simulado a partir de dos escenarios futuros de emisiones: el SRES A2 y el B2 (IPCC 2007).
Por otro lado, para analizar la viabilidad técnica de las estaciones de esquí, es decir teniendo en cuenta la capacidad de producir nieve, se ha utilizado el mismo criterio pero en este caso considerando el efecto de esta tecnología sobre la cobertura de nieve natural proyectada para cada estación. La Figura 3 muestra la vulnerabilidad natural y técnica (con nieve de producción) de las estaciones de esquí del Pirineo en el presente y bajo dos escenarios de cambio climático, uno medio y uno de más intensivo.

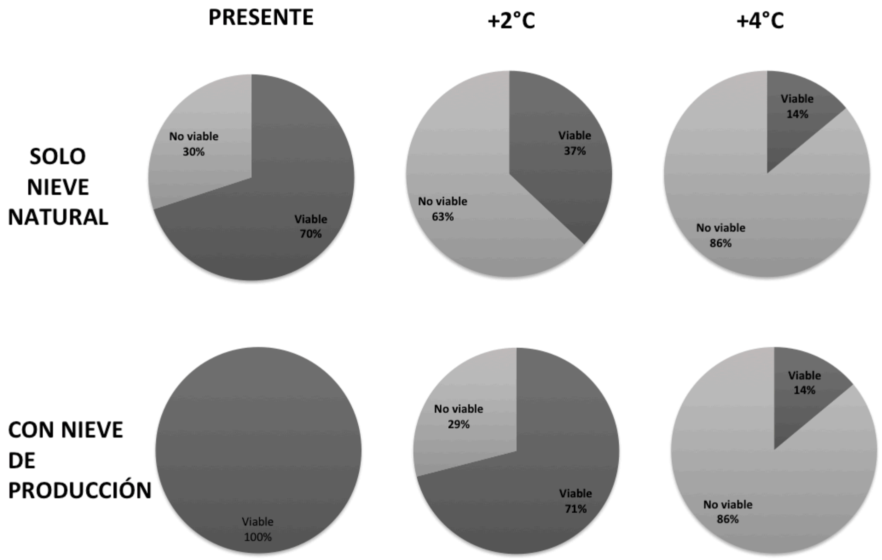


Figura 3. Viabilidad natural y técnica de las estaciones de esquí del Pirineo.

3.4.2- Impacto sobre la frecuencia de esquiadores

A partir de la proyección de los días esquiables en cada estación de esquí y de las estadísticas de visitantes obtenidas a partir de datos históricos de las estaciones (Datos propios obtenidos a partir de hemeroteca; DSF, 2012; ATUDEM, 2013 y SkiAndorra, 2013) y de los datos obtenidos a través de las encuestas de turismo de Andorra (Andorra Turisme, 2012), se ha proyectado la frecuentación de esquiadores en cada estación bajo los diferentes escenarios comentados anteriormente. Hasta día de hoy, la mayoría de estudios internacionales que han analizado los posibles impactos del cambio climático sobre el turismo de nieve consideraba que la disminución de esquiadores era proporcional a la disminución de días esquiables. Es decir, cuando una estación se considera no viable, se produce una pérdida del total de esquiadores. Sin embargo, estudios recientes han demostrado que solo una pequeña parte de estos esquiadores, entorno al 4%, dejaría de esquiar si cerrara la estación de esquí la cual frecuentan. El resto, mostraría una capacidad adaptativa ya sea mediante una sustitución espacial de la actividad (buscando la estación más cercana con las condiciones deseadas) o temporal (esquiando con más frecuencia durante los periodos que abra la estación) (Behringer et al., 2000; Dawson et al., 2011, Gössling et al, 2012; Dawson et al., 2013). Estos datos muestran la necesidad de incorporar este aspecto desde un punto de vista regional en los análisis de impacto ya que como se ha comentado anteriormente, el grado de los impactos del cambio climático sobre la cobertura de nieve puede ser muy heterogéneo a distancias muy cortas, y por consiguiente la vulnerabilidad de las estaciones de esquí de cualquier región. Con tal de poder incorporar la capacidad adaptativa de los esquiadores, se ha simulado la sustitución espacial y de actividad de los esquiadores cuando la estación la cual frecuentaban no dispone de las condiciones mínimas para operar. Ya que a día de hoy no se disponen de encuestas sobre la respuesta adaptativa de los esquiadores en el Pirineo, se han utilizado como referencia los datos de comportamiento de los estudios realizados en los Alpes y Norteamérica (Behringer et al., 2000; Dawson et al., 2011, Gössling et al, 2012; Dawson et al., 2013). Para estimar la sustitución espacial, se ha utilizado un modelo gravitacional georeferenciado que distribuye los esquiadores de una estación de esquí cerrada entre las disponibles en función de dos criterios: la distancia entre las estaciones de esquí y la capacidad de atracción de esquiadores de cada una de ellas. Para modelizar la capacidad de atracción de cada una de las estaciones se ha creado un indicador de atractividad en base a características físicas de las estaciones como la cota media o los kilómetros esquiables, y características socioeconómicas, como el precio del forfait o la oferta de actividades turísticas complementarias. El indicador creado representa de forma estadísticamente significativa ($R2 = 0,87$; $p\text{-value} < 0,01$) la distribución actual de esquiadores entre las estaciones de esquí de los Pirineos. De este modo, cuando una estación de esquí se considera no viable, un 4% de sus esquiadores se considera que cambia de actividad y el resto se redistribuye entre las estaciones de esquí restantes que seguirían operando siguiendo el modelo gravitacional. En un ejemplo hipotético, la posible redistribución de esquiadores según el modelo gravitacional cuando la estación de la Molina se encontrase cerrada, se observaría que una gran cantidad de esquiadores se desplazaría hasta Masella, debido al factor de proximidad y viceversa. Sin embargo, a pesar de que GrandValira se encuentra a mayor distancia que otras estaciones abiertas más próximas, se observa que esta estación absorbería un 11% de los esquiadores debido a su alta capacidad de atracción.

3.4.3 Clasificación de las estaciones de esquí según el nivel de vulnerabilidad

El modelo regional descrito nos permite analizar cómo los cambios locales proyectados sobre la cobertura de nieve van a impactar a nivel regional sobre el turismo de nieve en los Pirineos. Dicho análisis nos ha permitido identificar y clasificar en tres grupos las estaciones de esquí del Pirineo según su nivel de vulnerabilidad. El primer grupo está caracterizado por estaciones de esquí con un bajo nivel de atractividad turística y unas condiciones geográficas y climáticas menos favorables (estaciones a cotas más bajas, con una mayor influencia mediterránea y/o con orientaciones predominantes de sur,…). Este grupo muestra una disminución en el número de esquiadores tanto en un escenario de cambio climático medio (+2°C) como severo (+4°C), incluso con el uso de nieve de producción. Un segundo grupo, con un nivel de atractividad medio y con unas condiciones climáticas y geográficas más favorables que el primer grupo, muestra que bajo un incremento de cambio climático medio, es capaz de incrementar la frecuentación de esquiadores en su dominio en gran medida gracias a la nieve de producción. Sin embargo, bajo un escenario de cambio climático más severo, la mayoría de estaciones sufrirían un descenso de la frecuentación principalmente debido a la pérdida de días con las condiciones mínimas de temperatura para producir nieve de cultivo y por lo tanto de su capacidad de mantener una temporada más larga. Finalmente, el tercer grupo está caracterizado por estaciones con unas características geográficas privilegiadas (mayor altitud, mayor influencia atlántica y/o orientaciones predominantes de norte) y un mayor factor de atractividad turístico. Este grupo es considerado el más resiliente ya que a pesar de sufrir una reducción de la temporada de esquí, la capacidad de abrir durante más días que sus competidores y su mayor y más diversa oferta turística, les proporcionan una ventaja estratégica que les permitirá, tanto en un escenario de cambio climático moderado como en uno de más severo, atraer aquellos esquiadores de las estaciones de esquí cercanas más vulnerables.

La figura 4 muestra la evolución de la vulnerabilidad y del volumen de esquiadores bajo diferentes escenarios de cambio climático para tres estaciones diferentes del Pirineo. La figura muestra el comportamiento diferente de cada una de las tres estaciones según la clasificación obtenida mediante la metodología utilizada para este estudio: estaciones de alta vulnerabilidad, baja vulnerabilidad y resilientes.

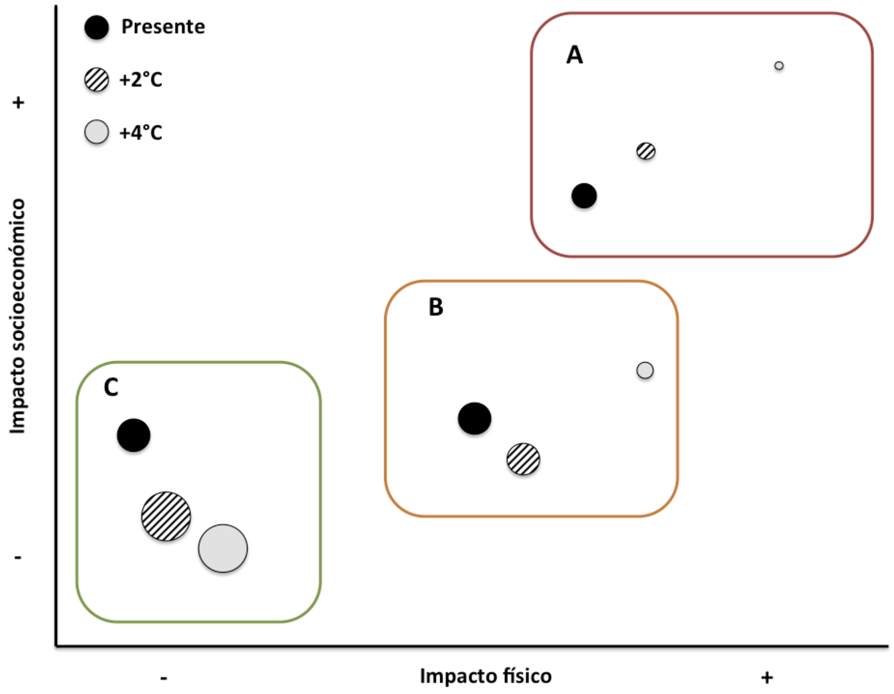


Figura 4. Evolución de los impactos negativos tanto económicos como físicos y del volumen de esquiadores (mayor tamaño, mayor frecuencia de esquiadores) en las estaciones A (alta vulnerabilidad), B (baja vulnerabilidad) y C (resiliente) bajo diferentes escenarios de cambio climático.

Estos resultados muestran y cuantifican por primera vez de forma objetiva que la principal consecuencia del cambio climático no será una disminución significativa del turismo de nieve sino una redistribución del turismo de nieve de las estaciones más vulnerables hacia aquellas estaciones más resilientes teniendo en cuenta no solo la variabilidad física y climática de cada una de las estaciones si no también la influencia de otros factores socioeconómicos como la oferta turística complementaria o la accesibilidad. Por otro lado, esta clasificación permite diferenciar vulnerabilidad de cada una de ellas y por lo tanto cuáles podrían ser las medidas de adaptación al cambio climático. De este modo, las estaciones de esquí identificadas como resilientes muy probablemente podrán continuar su actividad aplicando medidas de adaptación técnicas como la nieve de producción o la preparación de pistas. Sin embargo, debido a la capacidad de atraer nuevos esquiadores, seguramente deberán aplicar medidas para reducir y controlar el impacto sobre el entorno como consecuencia del incremento de actividad y del uso más intensivo que requerirán las medidas tecnológicas de adaptación, como puede ser el uso más intensivo de los cañones de nieve y sus repercusiones sobre los recursos energéticos y hídricos. El segundo grupo, identificado como de baja vulnerabilidad, podrá basarse a medio plazo en medidas de adaptación técnicas pero con una planificación futura basada en cambios más estructurales de su oferta turística como una mayor diversificación y desestacionalización de sus actividades. Finalmente, el grupo identificado como altamente vulnerable a los efectos del cambio climático, comprende aquellas estaciones las cuales deberían reconsiderar el turismo de nieve como su actividad principal y reorientarlo, en un marco de turismo sostenible, hacia otras actividades que no dependan tanto del recurso nivoso y estén más orientadas al turismo de montaña estival como por ejemplo el ciclismo de montaña, el turismo rural o el senderismo.

4. Conclusiones

En este proyecto de la CTP se ha conseguido por primera vez evaluar de forma objetiva la influencia del cambio climático en el turismo de nieve para la región del Pirineo. Debido al importante impacto económico y social de esta actividad era necesario tener un estudio de esta tipología que identificase la vulnerabilidad de las diferentes infraestructuras existentes. Cabe destacar por un lado, la heterogeneidad y gran variabilidad espacial de los resultados obtenidos indicando que no se puede generalizar los impactos y posibles soluciones para todas las estaciones. En ese sentido, la buena adaptación al cambio climático del sector pasará por acciones individualizadas para las diferentes estaciones en función del grado de la vulnerabilidad propia de cada una de ellas y del impacto esperado. Para las más resilientes, seguramente será suficiente con medidas de adaptación técnicas para garantizar su actividad. En cambio, las estaciones más vulnerables deberán basarse en soluciones más estructurales, fomentando las actividades complementarias, mejoras en las comunicaciones, la desestacionalización o en los casos más extremos, un completo cambio de actividad. Sin embargo cabe destacar que en la consecución de este proyecto se han identificado una serie de limitaciones y líneas futuras de investigación. Por un lado, la influencia que pueden tener factores como pueden ser el viento y otros fenómenos meteorológicos extremos en el funcionamiento de las instalaciones y las condiciones de esquiabilidad en una estación. Por otro lado, la importancia de tener en cuenta variables locales como la orografía, la orientación o la pendiente de las pistas ya que juegan un papel crucial en la distribución espacial de la nieve. En este sentido, en la actualidad se está desarrollando otro proyecto de la CTP: "Creación de un modelo de alta resolución espacial para cuantificar la esquiabilidad y la afluencia turística en el Pirineo bajo diferentes escenarios de cambio climático" con el objetivo de profundizar en estas líneas de trabajo y poder obtener unos resultados con un mayor grado de precisión y definición.

Agradecimientos:

Los autores de este trabajo agradecen la financiación del Govern d'Andorra (CTP-AND/2010), el Gobierno de Aragón y la Generalitat de Catalunya ralacionada con el proyecto de la CTP 2010-2012 y el Govern d'Andorra (CTP-AND/2012) y el Gobierno de Aragón la financiación del proyecto CTP2013-2014: "Creación de un modelo de alta resolución espacial para cuantificar la esquiabilidad y la afluencia turística en el Pirineo bajo diferentes escenarios de cambio climático". Marc Pons agradece al Gobierno de Andorra por una beca predoctoral [BTC2012/2013-0006-AND]. Se agradece también la información facilitada por Météo France refetene a los resultados del proyecto SCAMPEI.

BIBLIOGRAFIA

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

Andorra Turisme. 2012. Encuestas sobre actividad turística de los visitantes de el Principado de Andorra.

ATUDEM. 2013 *Dossier de premsa 2012-2013*. Associación Tursítica de Estaciones De Esquí y Montaña.

Barrera-Escoda, A., Cunillera, J. (2011) Projeccions de canvi climàtic per a Catalunya (NE Península Ibèrica). Part I: Modelització climàtica regional. Tethys, 8, pp. 77-89, doi: 10.3369/tethys.2011.8.08.

Behringer, J., Bürki, R., Fuhrer, J. (2000) Participatory integrated assessment of adaptation to climate change in alpine tourism and mountain agriculture. Integrated Assessment 1(3): 331–338

Beniston, M. (2003). Climatic change in mountain regions: A review of possible impacts. Climatic Change 59:5-31
DOI:10.1007/978-94-015-1252-7_2

Bicknell., S., McManus, P. (2006). The canary in the coalmine: Australian ski resorts and their response to climate change. Geographical Research 44:386-400
DOI: 10.1111/j.1745-5871.2006.00409.x

Breiling, M., Charamza, P. (1999). The impact of global warming on winter tourism and skiing: a regionalized model for Austrian snow conditions. Regional Environmental Change 1(1):4-14

Brunet, M., Casado, M.J, de Castro, M., Galán, P., López, J. A., Martín, J.M., Pastor, A., Petisco, E., Ramos, P., Ribalaygua, J., Rodríguez, E., Sanz, I., Torres, L. (2009). Generación de escenarios regionalizados de cambio climático para España. Madrid, Ministerio de Medio Ambiente y Medio Rural y Marino; Agencia Estatal de Meteorología. 158 pp.

Christensen, O.B., Christensen, J.H., Machenhauer, B., Botzet, M., (1998). Very high resolution regional climate simulations over Scandinavia-present climate.
Journal of Climate 11, 3204–3229.
doi: http://dx.doi.org/10.1175/1520-0442(1998)011<3204:VHRRCS>2.0.CO;2

Dawson, J., Scott, D. (2010). Systems analysis of climate change vulnerability for the US Northeast ski sector. Tourism Planning and Development 7(3):219-235
http://dx.doi.org/10.1080/1479053X.2010.502383

Dawson, J., Havitz, M., Scott, D. (2011). Behavioral Adaptation of Alpine Skiers to Climate Change: Examining Activity Involvement and Place Loyalty', Journal of Travel & Tourism Marketing, 28: 4, 388-404.
http://dx.doi.org/10.1080/10548408.2011.571573

Dawson, J., Scott, D., Havitz, M. (2013). Skier demand and behavioural adaptation to climate change in the US Northeast. Leisure/ Loisir, 37(2), 127-143.
http://dx.doi.org/10.1080/14927713.2013.805037

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

El Kenawy, A., López-Moreno, J.I., Vicente-Serrano, S.M. (2012) Trend and variability of temperature in northeastern Spain (1920-2006): linkage to atmospheric circulation. Atmospheric Research 106: 159–180.
http://dx.doi.org/10.1016/j.atmosres.2011.12.006

Elsasser, H., Bürki, R (2002). Climate change as a threat to tourism in the Alps. Climate Res 20:253-257
http://dx.doi.org/10.3354/cr020253

ESCAT, Generació d'escenaris climàtics amb alta resolució per a Catalunya (Resum executiu). (2012). Servei Meteorològic de Catalunya. Departament de Territori i Sostenibilitat. Generalitat de Catalunya.

Esteban P., Prohom Duran M., Aguilar E., (2012) Tendencias recientes e índices de cambio climático de la temperatura y la precipitación en Andorra, Pirineos (1935-2008) Pirineos, 167 (2012)
doi:10.3989/Pirineos.2012.167005

Fukushima, T., Kureha, M., Ozaki, N., Fujimori, Y., Harasawa, H (2003). Influences of air temperature change on leisure industries: case study on ski activities. Mitigation and Strategies for Climate Change 7:173-189

Gössling, S., D. Scott, C., Michael Hall, J.-P. Ceron and Dubois, G. 2012. Consumer behaviour and demand response of tourists to climate change. Annals of Tourism Research, 39(1): 36-58.
http://dx.doi.org/10.1016/j.annals.2011.11.002

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, Australia

Hendrikx, J., Hreinsson, E. Ö, Clark, M.P., Mullan, A.B. (2012). The potential impact of climate change on seasonal snow in New Zealand: part I-an analysis using 12 GCMs. Theoretical and Applied Climatology, 110 (4), 607-618
http://dx.doi.org/10.1007/s00704-012-0711-1

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

Intergovernmental Panel on Climate Change IPCC (2013) Climate change 2013: synthesis report. Summary for policy makers. Fifht Assessment Report. United Nations Intergovernmental Panel on Climate Change, Geneva

Keller, F., Kienast, F., and Beniston, M. (2000) Evidence of the Response of Vegetation to Environmental Change at High Elevation Sites in the Swiss Alps. Regional Env. Change 2, 70–77.
10.1007/PL00011535

Keller, F., Goyette, S., Beniston, M. (2005). Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. *Climatic Change* 72:299-319
http://dx.doi.org/10.1007/PL00011535

König, U., Abegg, B. (1997). Impacts of climate change on tourism in the Swiss Alps. Journal of Sustainable Tourism 5(1):46-58
http://dx.doi.org/10.1080/09669589708667275

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

Lasanta, T., Laguna Marín-Yaseli, M., Vicente-Serrano, S.M. (2007). Do tourism-based ski resorts contribute to the homogeneous development of the Mediterranean mountains? A case study in the Central Spanish Pyrenees. Tourism Management, 28(5): 1326-1339.
http://dx.doi.org/10.1016/j.tourman.2007.01.003

Lasanta, T., Laguna Marín-Yaseli, M., Vicente-Serrano, S.M. (2007b). Variabilidad especial de los efectos socioeconómicos de las explotaciones de esquí alpino en los municipios rurales del Pirineo aragonés. Pirineos 162: 155-176.

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
http://dx.doi.org/10.1016/j.jhydrol.2009.06.049

McBoyle, G., Wall, G. (1987). The impact of CO2 induced warming on downhill skiing in the Laurentians. Cahiers de géographie du Québec 31(82):39-50
http://dx.doi.org/10.7202/021843ar

Moen, J., Fredman, P. (2007), Effects of Climate Change on Alpine Skiing in Sweden. Journal of Sustainable Tourism 15(4):418-437
http://dx.doi.org/10.2167/jost624.0

Pons-Pons, M., Johnson, P.A., Rosas-Casals, M., Sureda, B., Jover, È. (2012). Modeling climate change effects on winter ski tourism in Andorra. Clim Res 54:197-207
http://dx.doi.org/10.3354/cr01117

SCAMPEI (2012). Scénarios climatiques adaptés aux zones de motagnes: Phénomènes extrêmes, enneigement et inCertitudes. http://www.cnrm.meteo.fr/scampei/

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. Climate Res 23:171-181
http://dx.doi.org/10.3354/cr023171

Scott, D., McBoyle, G., Minogue, A. (2007). Climate change and Quebec's ski industry. Global Environmental Change 17:181–190.
http://dx.doi.org/10.1016/j.gloenvcha.2006.05.004

Scott, D., Gössling, S., Hall, C.M. (2012). Climate Change and Tourism: Impacts, Adaptation and Mitigation. London: Routledge. 423 pgs.

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

Steiger R, Mayer M (2008) Snowmaking and climate change. Future options for snow production in Tyrolean ski resorts. *Mt Res Dev* 28, 292–298 http://dx.doi.org/10.1659/mrd.0978

Steiger, R. (2010). The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Climate Research, 43(3),* 251-262
http://dx.doi.org/10.3354/cr00941

Steiger, R. (2012). Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, 20(6), p. 867–882
10.1080/09669582.2012.680464

Steiger, R., Abegg. B. (2013) The sensitivity of Austrian Ski areas to climate change. Tourism, planning and development, 480-493.
http://dx.doi.org/10.1080/21568316.2013.804431

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
http://dx.doi.org/10.1002/joc.1786

Vanat, L. (2013)2013 International Report On Snow & Mountain Tourism.

Witmer, U., 1986. Erfassung, Bearbeitung und Kartierung von Schneedaten in der Schweiz. GeographicaBernensia G25.

UNWTO-UNEP (2003) Climate change and tourism. Proceedings of the First International Conference on Climate change and Tourism, Djerba, 9-11 April. Madrid: World Tourism Organization.

APPENDIX B. IMPACT OF THE RESEARCH ON THE MEDIA

Cambio climático y el Esquí. Para Todos la 2. RTVE. 10/1/2014
http://www.rtve.es/alacarta/videos/para-todos-la-2/para-todos-2-debate-cambio-climatico-esqui/2297872/

Diari Forum. 11/11/2013
http://forum.ad/2013/11/11/lobsa-treballa-sobre-la-influencia-del-canvi-climatic-en-el-turisme-de-neu/

Rescat a l'esquí. 30 minuts. Televisió de Catalunya TV3. 23/03/2013
http://www.tv3.cat/30minuts/reportatges/1874/Rescat-a-lesqui

Diari EL Punt Avui. 26/3/13
http://www.elpuntavui.cat/noticia/article/2-societat/5-societat/631602-el-canvi-climatic-posara-en-risc-les-estacions-desqui-per-sota-de-2000-metres.html?tmpl=component&print=1&page=

Terrassa Digital. 21/3/2013
http://www.terrassadigital.cat/detall_arxiu/?id=15674

Sala de premsa UPC. 20/3/2013
http://www.upc.edu/saladepremsa/al-dia/mes-noticies/investigadors-del-campus-de-terrassa-avaluen-la-influencia-del-canvi-climatic-a-les-pistes-d2019andorra

Nació Digital 20/3/2013
http://www.naciodigital.cat/noticia/52958/andorra/pais/sense/neu

Editorial Diari d'Andorra. 1/2/2013
http://www.diariandorra.ad/index.php?option=com_k2&id=22858&view=item&Itemid=534

Can Snow machines fix Andorra's slippery slopes?
ClimateWire. The politics and business of climate change. E&E Publishing Services.
31/1/2013.
http://www.eenews.net/cw/2013/01/31

Radio Seu. 31/1/2013
http://www.radioseu.cat/not%C3%ADcies/Medi+Ambient/L'estudi+andorrà+sobre+el+canvi+climàtic+preveu+augments+de+la+temperatura+mitjana

Climate News Network. 29/01/2013
http://www.rtcc.org/2013/01/29/andorra-contemplates-slopes-with-no-snow-if-warming-rises-above-2c/

El Tiempo 24. 29/1/2013
http://www.eltiempo24.es/noticias/2013/01/29/el-cambio-climatico-podria-provocar-perdidas-millonarias-en-las-estaciones-de-esqui-del-pirineo/
Science News. 28/1/2014
http://www.science-news.eu/environment-news/cluster236667/

Cadena Ser. Participació projecte govern de Canadà. 12/11/2013 http://www.cadenaser.com/canarias/audios/l-observatori-sostenibilitat-d-andorra-participara-projecte-canadenc-canvi-climatic-horal-12-11/csrcsrpor/20131112csrcsrcan_1/Aes

Science Daily sobre l'impacte del canvi climàtic al turisme de neu als Pirineus. 23/1/2013
http://www.sciencedaily.com/releases/2013/01/130123094259.htm

Eureka Alert. AAAS. 23/3/2013
http://www.eurekalert.org/pub_releases/2013-01/f-sf-ccc012313.php

Cambioclimatico.com. 22/1/2013
http://climaticocambio.com/tag/esqui/

Agencia de Servicios de Información y Notícias Científicas (SINC) del FECYT, Ministerio de eceonomía y competitividad. Gobierno de España. 22/1/2013
http://www.agenciasinc.es/Noticias/El-cambio-climatico-podria-provocar-perdidas-millonarias-en-las-estaciones-de-esqui-del-Pirineo

Periòdic d'Andorra. 17/11/2012
http://www.elperiodicdandorra.ad/societat/24111-les-estacions-desqui-es-preparen-per-fer-front-al-canvi-climatic-.html?utm_source=dlvr.it&utm_medium=facebook

Diari d'Andorra. 14/5/2012
http://diariandorra.ad/index.php?option=com_k2&view=item&id=20051&Itemid=435

El canvi climàtic, un repte. Diari d'Andorra. 19/2/2012
http://diariandorra.ad/index.php?option=com_k2&id=18320&view=item&Itemid=541

6th Credencials TV show. Martí Boada and Marc Pons. Televisió d'Andorra. 25/2/2014
http://194.158.80.30/media/credencials-marc-pons-i-marti-boada
https://www.youtube.com/watch?v=ZTE-YWsK65U