Vol. 54: 197–207, 2012
doi: 10.3354/cr01117

CLIMATE RESEARCH
Clim Res

Published online October 11

Modeling climate change effects on winter ski tourism in Andorra

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ABSTRACT: Mountain regions have been identified as especially vulnerable areas to climate change. Changes in snowfall, glacier retreat and shifts in levels and distribution of biodiversity 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. We project a reduction in ski season length and a drop in 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 only be considered as a suitable short-term strategy, rather than 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 designing and developing appropriate sustainable adaptation strategies to future climate variability.

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

1. INTRODUCTION

Mountain regions have been identified as especially vulnerable to climate change. The rapid retreat of glaciers, changes in amount and frequency of snowfall, and shifts in the levels and distribution of biodiversity, 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 (WTO 2003, IPCC 2007, CADS 2010). In recent years many studies have analyzed the impacts of climate change on the ski industry in regions such as the European Alps (Abegg 1996, König & Abegg 1997, Breiling & Charamza 1999, Elsasser & Bürki 2002, Steiger & Mayer 2008, Uhlmann et al. 2009, Chaix 2010, Steiger 2010, Töglhofer et al. 2011), Canada (McBoyle & Wall 1987, Lamothe & Périard 1988,

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Scott et al. 2003, 2006, 2007), USA (Lipski & McBoyle 1991, Dawson & Scott 2007, 2010, Scott et al. 2008, Dawson et al. 2009), Sweden (Moen & Fredman 2007), Australia (Galloway 1988, Hennessy et al. 2003, Bicknell & McManus 2006), Japan (Fukushima et al. 2002), 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 ~80 000 inhabitants and an area of 468 km^2. Andorra receives >10 million tourist visits every year (Andorra Turisme 2010). Hence winter tourism is presented as one of the main income sources and the 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 snowmaking. It is critical to assess not only 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 (Scott et al. 2007, CADS 2010, Yang & Wan 2010). This study analyzed 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 geo-referenced 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 (Torrens 2003, Berger & Schreinemachers 2006, Ligmann-Zielinska & Jankowski 2007). 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 ABMs have been used to analyze a broad spectrum of spatial phenomena such as water and agriculture management (Feuillette et al. 2003, Bithell & Brasington 2009, Smajgl et al. 2009), the dynamics in ancient human and primate societies (Axtell et al. 2002, Janssen 2009), land use and land cover change (Parker et al. 2003, Deadman et al. 2004, Manson & Evans 2007), 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 geo-referenced ABM to model tourism phenomena. Gimblett & Skov-Petersen (2008) and Itami et al. (2002) used ABM for the simulation and visualization of visitor patterns of movement in recreational landscapes such as parks and protected areas. In addition, Johnson & Sieber (2009, 2010, 2011) developed an ABM of tourism dynamics in the Canadian province of Nova Scotia. The model, designed as a Planning Support System (PSS), simulates the movement, destination preferences and interactions of tourist agents across a geo-referenced landscape of 35 main tourist destinations.

Geo-referenced ABM can also be seen as a type of 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 was 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 decline in the number of skiers and in their expenditure in the region. Moreover, the scenarios generated by the model also take into account the effects of 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.

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 geo-referenced ABM that simulates an average winter season and relates the climate change impacts on the snow cover with their socioeconomic implications in the region such as season length, skiers and expenditure reductions in 3 different scenarios: one present scenario and 2 future scenarios assuming a 2 and 4°C increase of the winter average temperature. Fig. 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 snow production systems in the enhancement of the natural snow cover. The resulting snow cover at each ski resort is the dynamic component of the environment where the agents, the ski visitors in our model, interact and make decisions on the basis of both their internal and snow cover states.

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.

2.1. Environment

The environment, i.e. the space where the agents interact and respond to its changes, is implemented using 4 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 surface area of the 3 ski resorts: Grand-Valira, Arcalís and Pal-Arinsal (Fig. 2). This latter layer changes over time on the basis of snow cover conditions and determines the season length according to the daily snowpack available in the resort. The first 3 layers remain static during the simulation.

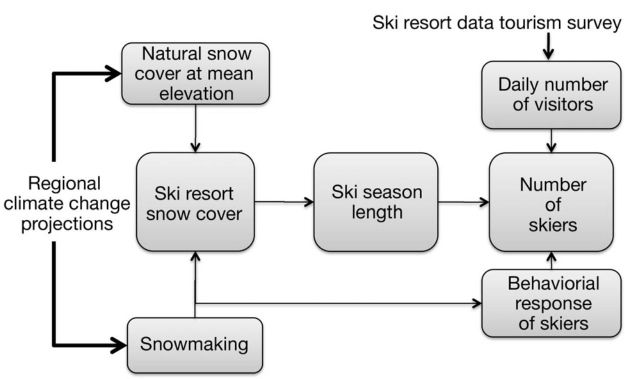

Fig. 1. Conceptual map of the model

2.1.1. Natural snow cover and season length

The future natural snow cover at each ski resort was modeled using the projected changes in the Pyrenean daily snowpack during the 21st Century from López-Moreno et al. (2009). This study simulated 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 were based on 2 future emissions scenarios: the SRES A2 and B2 scenarios (IPCC 2007) for different altitudinal levels: 1500, 2000, 2500 and 3000 m. This model gives a good agreement in the overall snow depth and duration between the observed and the simulated snowpack. The ski season length was simulated using the snowpack projection in a reference elevation range for 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 (Witmer 1986, Abegg 1996, Scott et al. 2003, Abegg et al. 2007, Dawson & Scott 2007, 2010, Scott & McBoyle 2007, Chaix 2010, Steiger 2010). This refers to a standard definition for snow reliabil-

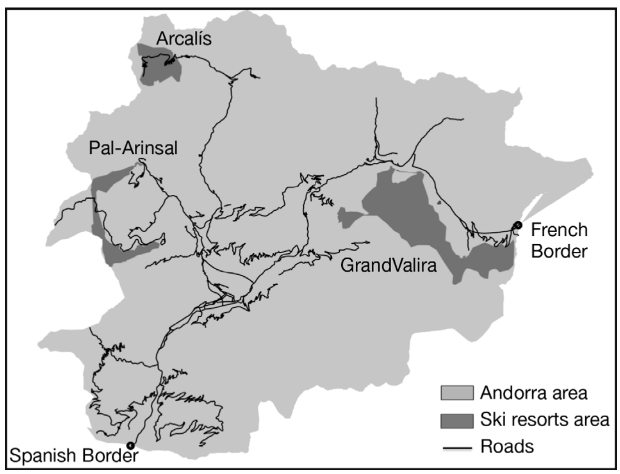

Fig. 2. GIS layers used as dynamic environment for the Agent Based Model

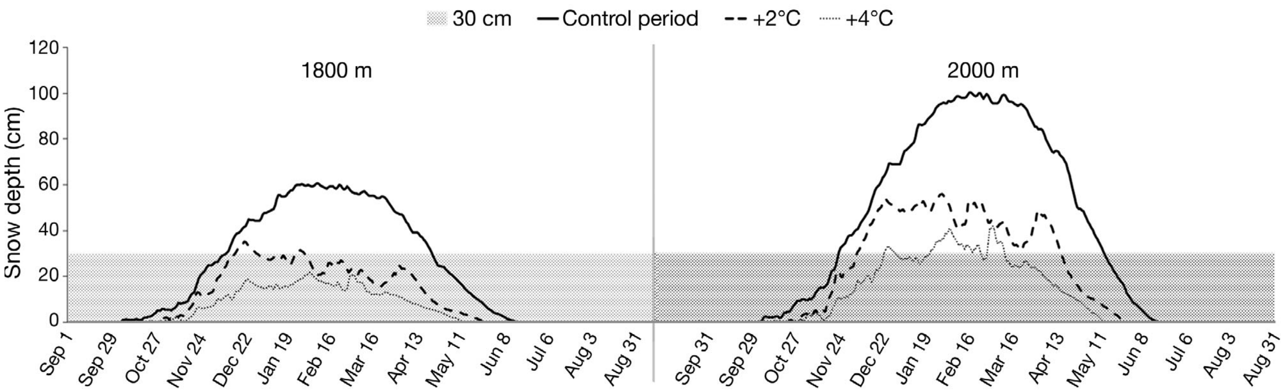

Fig. 3. Mean control period (1960-1990) and future (+2 and +4°C scenarios) snow depth in Pal-Arinsal at 1800 and 2000 m

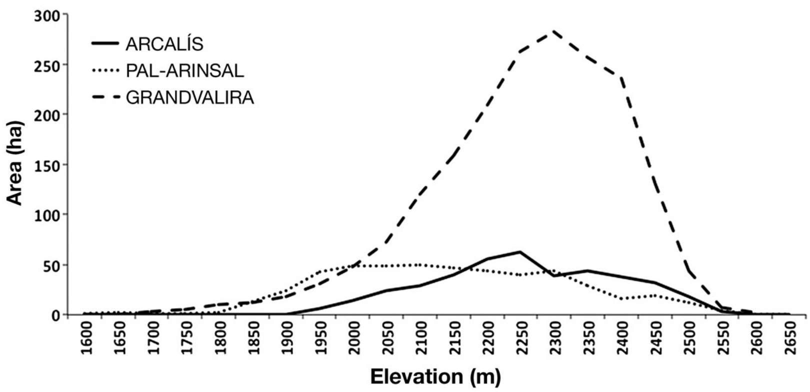

Fig. 4. Altitudinal distribution of the Andorran ski resorts

ity assuming that 100 d 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. Fig. 3 shows the mean control period (1960 to 1990) and future snow cover in Pal-Arinsal (assuming a 2 and 4°C increase of the winter average temperature) at 1800 and 2000 m of elevation. The grey area marks the 30 cm threshold showing those days in which 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.

The altitudinal distribution of each ski resort has been identified in order to assign an elevation range. As shown in Fig. 4, 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. Because of that, the reference values have been assigned selecting the lowest and the highest elevation in which most of the ski resort area (75%) is concentrated. Thus, the altitudinal ranges assigned are 1900–2300 m for Pal-Arinsal, 2100–2400 for Arcalís and 2150–2450 m for GrandValira. These ranges permit an analysis of the extent of potential impacts for each ski resort in relation to their elevation range.

Once the altitudinal range has been defined, a daily snow cover is assigned for each elevation based on the projected snowpack from López-Moreno et al. (2009). Because the snow projections from this study are presented every 500 m (1500, 2000, 2500 and 3000 m), a linear interpolation was needed between these elevations in order to achieve a finer resolution of the altitudinal variability.

2.1.2. Snowmaking module

Over the last few decades, ski resorts across the world have invested significant amounts of money in snow production systems (Steiger & Mayer 2008), and ~50% of the Andorran ski area is now covered by snow production systems (http://vallnord.andorramania.com, http://grandvalira.andorramania.com). This adaptation strategy is intended to offset the variability of snowfall, guaranteeing good skiing conditions, scheduled openings and stable revenues (Steiger & Mayer 2008). 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, snowmaking has been simulated only to a degree that assures the minimum snow depth that is required for skiing. For the highest and lowest elevations that define the altitudinal range of the ski resort, the module simulates a maximum of 10 cm snow production on each day for which the natural snow cover is below the 30 cm threshold (Scott et al. 2003, Steiger 2010). Only those days with a minimum temperature of –5°C are considered as potential snowmaking days (Steiger & Mayer 2008). Thus, a new snowpack and resulting season length is achieved by adding the effect of the snowmaking on the natural snow cover for each elevation. Fig. 5 shows the enhancement of the natural snow cover at 1900 m in Pal-Arinsal following the defined parameters for a +2°C climate change scenario.

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 2 main entities: the skiers, the agents of our model, and the ski resorts, which are fixed on the landscape. Skiers include the following attributes: (1) point of entry to Andorra, (2) visitor type (whether they are 1 day visitors or overnight visitors), (3) mean daily expenditure, (4) destination ski resort and (5) 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 percentages of these features obtained from the winter-month data from the national tourism survey (Andorra Turisme 2010). This survey represents a sample of 4010 international visitors and intends to capture the frequency, seasonality, nationality, activities and accommodation preferences of all kind of Andorra visitors during winter, spring, summer and fall seasons. The location coordinates attribute is updated throughout the simulation according to where the skier is in each time step. Ski resorts have the following attributes: (1) ski season length in d, (2) state (whether it is open or closed), (3) location coordinates and (4) reference elevation.

The ski season length and the status of the resorts change throughout the simulation according to the projected snow cover.

2.2.1. Process overviewing and scheduling

This section defines the actions of each entity, the order in which they are executed, and when the different state variables are updated. Fig. 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 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 daily agents are created based on the average values of tourist arrivals from the 2000-2010 national tourism surveys statistics in order to simulate the daily arrival of skiers. The value of the daily number of arrivals will be different each day representing seasonality due to peak and holiday periods such as Christmas and Easter.

Once these agents (skiers) have been created, they each follow the sequence described in Fig. 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 assigned to a border entry point and a visitor type based on the real statistical share of the feature. Using values drawn from the tourism surveys, 73% of the agents will be randomly assigned as 1 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 d, and a value of 1 for 1-day visitors. In order to compute the daily and total expenditure of the skiers and simulate the difference in the mean expenditure of each type of visitor, the model assigns a value of 173 euros for overnight visitors and 110 euros for 1-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

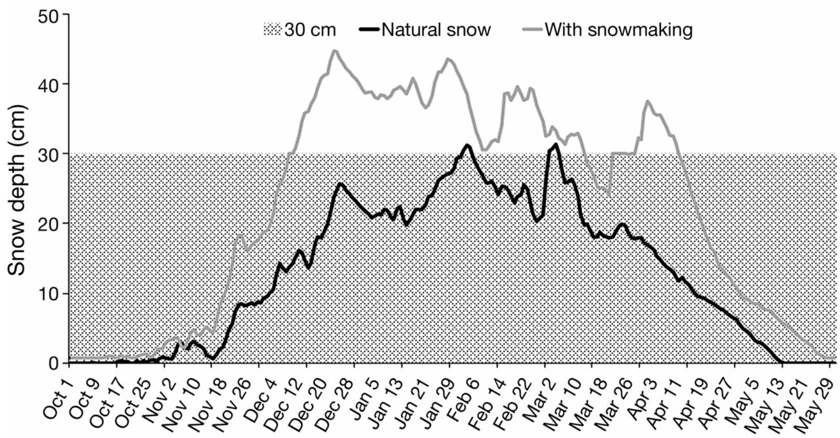

Fig. 5. Enhancement of natural snow cover with snowmaking at 1900 m in Pal-Arinsal assuming a 2°C increase in mean winter temperature

with the statistical values obtained from the national tourism survey of Andorra (Andorra Turisme 2010).

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 1 d the value of this attribute. The agents with a new value of 0, that is, those that were 1-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 d and, simulations run for 151 d, from 1 December to 30 April, an entire winter season in Andorra.

3. RESULTS

In order to analyze the future impact of climate-change-induced snow reductions on the Andorra ski industry, 4 different scenarios were run. The 2 first scenarios assumed an increase in the winter mean temperature (November to April) of +2 and +4°C, respectively. The other 2 scenarios added the effect of the potential snowmaking on enhancing the natural snow cover and extending the season in the +2 and +4°C base scenarios. The resulting number of skiers in the 3 ski resorts of Andorra (GrandValira, Arcalís and Pal-Arinsal) was compared with the values of a reference period. In order to avoid monthly attendance comparison with a single refence year with unusual weather conditions, mean values for the attendance of skiers in the reference-control period have been smoothed by

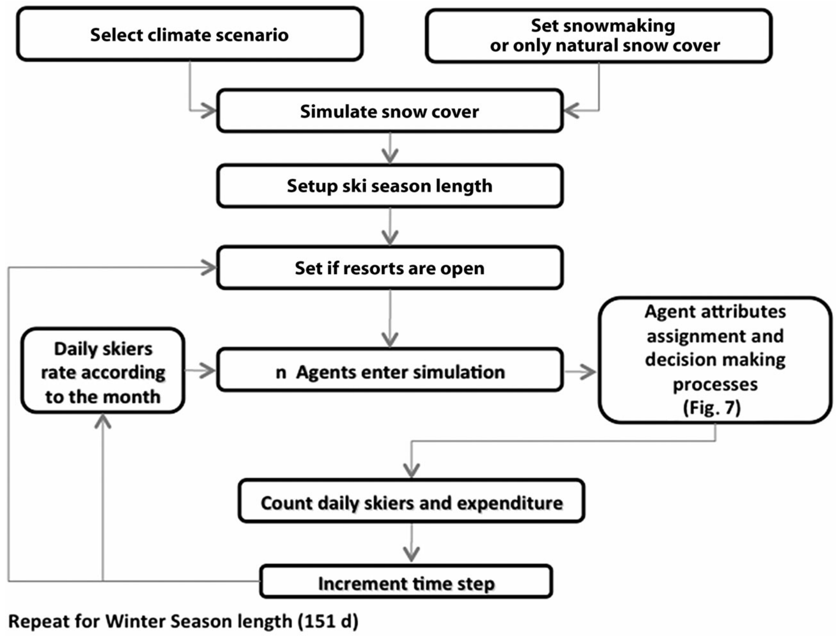

Fig. 6. Model processes flowchart

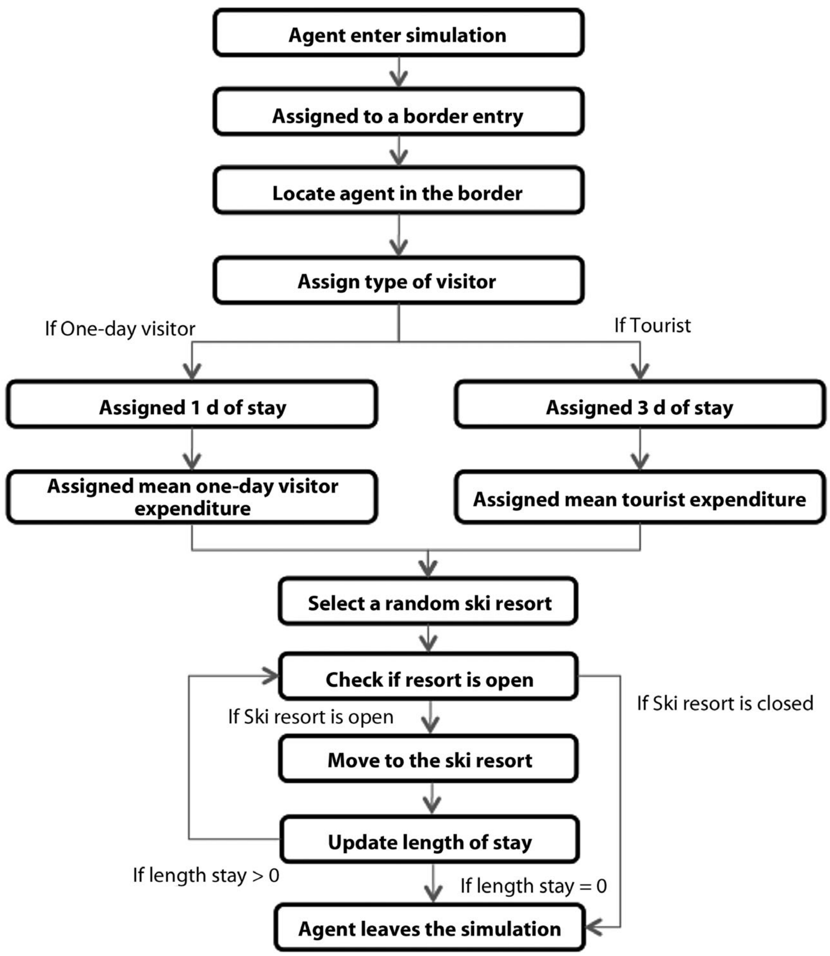

Fig. 7. Agents' decision-making and attribute assignment flowchart

the average number of skiers for each month from 2000 to 2010.

3.1. Impact on ski season length

In order to achieve a range of potential impacts, the average values for the control period were compared with the projected future season length in the low and high reference elevations for each ski resort. Fig. 8 shows the projected season for an average winter in Andorra at the different elevation ranges of the ski resorts. In the scenario assuming an increase of 2°C, only the lowest part of Pal-Arinsal is significantly affected by a reduction in the season length (30%), mainly at end of the season when snowfall is more erratic (Table 1). The higher parts of this resort and the other 2 resorts, with most of their ski area located at higher elevations (>2100 m), are not affected by this particular climate change scenario. Only the lowest area of Arcalís is affected by a minor reduction of 3%. Comparing this with a scenario of +2°C that includes snowmaking, the season length in Pal-Arinsal would be increased by 5% (still 25% shorter than in the reference period), and no change in Arcalís. In the scenario assuming an increase of 4°C, all 3 ski resorts would suffer serious reductions in the lower areas. The Pal-Arinsal season would be almost entirely reduced (95%) whereas GrandValira and Arcalís would suffer reductions of 17 and 27% respectively. The higher parts of the 3 ski resorts would remain reliable for almost the whole season. Only the highest area of Pal-Arinsal would be affected by a 3% reduction. Unlike the +2°C scenario, snowmaking would not help to significantly alleviate these reductions with the 4°C scenario. Since low temperatures are required to efficiently produce snow, the capacity of snowmaking to extend the season at low elevations is highly reduced under a +4°C scenario. The potential number of days on which snow could be produced at lower elevations (i.e. where snow production is most needed) would be significantly reduced.

Applying the 100-day rule, the lowest parts of all 3 ski resorts would remain reliable with an increase of 2°C. In contrast, with an increase of 4°C, Pal-Arinsal would not be reliable even with snowmaking, whereas the other 2 resorts would remain reliable despite the projected season reductions. None of the future climate projections would significantly affect the reliability at the highest elevations of all ski resorts located in Andorra.

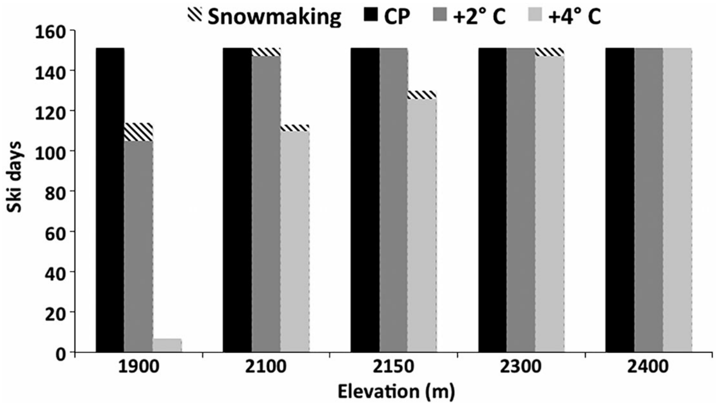

Fig. 8. Ski days in an average winter season with natural snow cover and with snowmaking in the control period (CP) and assuming a 2° and 4°C increase in winter average temperature

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 in the total number of skiers in Andorra under the different scenarios presented in the previous section. In order to analyze the potential range of the skiers reduction at a regional scale, a maximum and minimum value have been estimated based on the extent of the impact at the 2 reference elevations of each ski resort. Thus, the

Table 1. Projected average change in ski season length (%) at selected minimum and maximum elevation for each ski resort

Ski Resort	Elevation (m)	Change in ski season length (%) +2°C Natural snow cover	+2°C With snowmaking	+4°C Natural snow cover	+4°C With snowmaking
Pal-Arinsal	1900	−30	−25	−95	−95
	2300	0	0	−3	0
Arcalis	2100	−3	0	−27	0
	2400	0	0	0	0
Grand Vilara	2150	0	0	−17	−14
	2450	0	0	0	0

Table 2. Projected changes (%) in total number of skiers

Scenario	Change in total number of skiers (%) Natural snow cover Max	Mean	Min	Snowmaking Max	Mean	Min
+2°C	−4.4	−2.2	0.0	−3.2	−2	0
+4°C	−30.2	−15.2	0.2	−26.2	−13	0

maximum skier reductions are estimated based on the projected impact on season length at low elevations, and the minimum based on the impact at the high reference elevations. In a +2°C scenario, a small drop in the number of skiers and their expenditure occurs because only the lowest area of Pal-Arinsal would be affected. On the other hand, the +4°C scenario indicates a more severe drop (15% reduction on average) that would lead to a mean loss of skier-related revenue of ~50 million euros (value 2009) per season. In this case, the 2 ski resorts with higher visitor numbers (Pal-Arinsal and GrandValira) would be affected both at the beginning and at the end of the season, increasing the extent of the impacts. Finally, for a +4°C scenario, when the decrease in the number and expenditure of skiers is marked, snowmaking has little effect regionally, knocking only ~2 percentage points off the 15.2% reduction in the number of skiers that occurs without snowmaking.

4. DISCUSSION

The objective of this study was to understand the climate change vulnerability of the Pyrenean winter tourism industry by means of a geo-referenced ABM. The findings of the study are in line 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 lower elevations of the Andorra ski resorts. 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 >2000 m) in relation to other affected ski areas in Europe. On the other hand, snowmaking could help to extend and provide reliable season lengths with a mid-range climate change scenario. However, due to the projected increase in the minimum and average temperature, the derioration in conditions with regard to efficient artificial snow production will become a future constraint. Therefore, in line with previous studies, snowmaking cannot completely solve the problem of ensuring snow cover in Andorra at lower elevations, and should be considered as a suitable short-term strategy, but not as a sustainable long-term adaptation strategy (Scott & McBoyle 2007, Bark et al. 2010, Steiger 2010). In addition to being climatically marginal, snowmaking could entail future constraints in terms of security of water supplies, ecosystem alteration, and infrastructure and energy costs associated with large increases in snowmaking volumes. Even if they are climatically viable (in the sense of ensuring the climatic conditions for which snow can be efficiently produced), these constraints can turn snowmaking into an uneconomic adaptation strategy for some ski operators, and an unacceptable state of affairs for the ecosystem services in some regions (Hahn 2004, Scott & McBoyle 2007, Steiger & Mayer 2008, Rixen et al. 2011).

Our results should be taken as future general trends and not as accurate predictions for the Andorra ski resorts. The 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 resort 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, we expect model skill to be improved by refining the variables and parameters through 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

One of the greatest challenges in this kind of analysis is in relating projected physical impacts in ski areas to socioeconomic indicators, such as the shifts in skiers attendance or ski resort revenues because of snow cover alteration (Dawson et al. 2009). One of the main reasons to use a geo-referenced ABM was precisely to achieve a more detailed assessment of the socioeconomic dimension. The georeferenced ABM methodology used in this study demonstrates its potential as a tool to simulate the climate change impacts on winter tourism, and particularly to analyze the interaction between physical changes (snowpack and resulting season length) and socioeconomic implications (the potential loss of both skiers and their economic expenditure in the region). Compared to most of the models published to date, our methodology includes behavioral responses and heterogeneity of the winter tourist profile. This is relevant to this type of study, since — as a result of changing snow conditions — (1) changes in individual skiing behavior are more frequent than changes in the structure and/or managerial strategies of ski resorts, usually difficult to implement in terms of cost and time (Dawson et al. 2009); and (2) in tourism modeling, visitors cannot be grouped as a single aggregated class with 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 as the impacts on a regional scale.

The use of a geo-referenced landscape made it possible to capture the intrinsic spatial features of tourism phenomena. In our case, the ski resort location and elevation have been taken into account with this approach. Future developments must take into account the influence of other geographical parameters such as travel distances or specificities of the tourism destination landscape such as slope orientation. Future areas of refinement must focus on increasing the heterogeneity of the agents (skiers) by including ski level or activity involvement, and different behavioral response to environmental changes on the basis of their profile.

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, Fukushima et al. 2002, Hamilton et al. 2007, Unbehaun et al. 2008, Shih et al. 2009, Dawson et al. 2011, Pütz et al. 2011).

Acknowledgements. The authors are thankful to Dr. I. 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. M.P.P. also acknowledges a predoctoral grant from Government of Andorra and Crèdit Andorrà Foundation, BTC2010/2011-0006-AND.

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Editorial responsibility: Helmut Mayer, Freiburg, Germany

Submitted: January 30, 2012; Accepted: June 13, 2012
Proofs received from author(s): September 28, 2012