Effects of meteorological variability and climate change on ski tourism in the Spanish Central Pyrenees and Andorra: analysis of trends and future scenarios.

Tesis doctoral/PhD Dissertation

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Universidad San Jorge

Instituto Pirenaico de Ecología (CSIC)

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Effects of meteorological variability and climate change on ski tourism in the Spanish Central Pyrenees and Andorra: analysis of trends and future scenarios

Efectos de la variabilidad meteorológica y el cambio climático sobre el turismo de esquí en el Pirineo Central español y Andorra: análisis de tendencias y escenarios de futuro

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Memoria presentada para optar al título de Doctora por:

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Certifican:

Que el trabajo de investigación recogido en la presente memoria titulada: **"***Effects of meteorological variability and climate change on ski tourism in the Spanish Central Pyrenees and Andorra: analysis of trends and future scenarios***"** (*Efectos de la variabilidad meteorológica y el cambio climático sobre el turismo de esquí en el Pirineo Central español y Andorra: análisis de tendencias y escenarios de futuro)*; Que será presentada en la Universidad San Jorge, ha sido realizado bajo su dirección, así como en el Instituto Pirenaico de Ecología del CSIC de Zaragoza, por María Gilaberte Búrdalo y autorizan su presentación para optar al grado de Doctor. Y para que conste, firmamos el presente certificado en Villanueva de Gállego (Zaragoza), a 5 de diciembre de 2017.

Dr Juan Ignacio López Moreno   Dr Fernando López Martín   Dra Rosa Pino Otín

A la memoria de mi padre, a mi madre, a mi hermano

y a Dani

List of Acronyms and Abbreviations:

AEMET- Agencia Estatal de Meteorología

ANOVA- Analysis of Variance

AOGCM - Atmosphere-Ocean coupled General Circulation Models

AR - Assessment Report

ASWE - Accumulated Snow Water Equivalent

ATUDEM-Asociación Turística de Estaciones de Esquí y de Montaña

CC- Climate Change

CEDEX - Centro De estudios y Experimentación de Obras Públicas (Ministerio de Fomento)

CRHM – Cold Regions Hydrological Model

ECMWF- European Centre for Medium-Range Weather Forecasts

FAR - First Assessment Report

GDP - Gross Domestic Product

GHG - Greenhouse Gas

HCI- Holiday Climate Index

IPCC - Intergovernmental Panel on Climate Change

MM - Mesoscale Model

NAO- North Atlantic Oscillation

NGO - Non-governmental organization

OECC- Oficina Española de Cambio climático

OECD- Organisation for Economic Co-operation and Development

PCA- Principal Components Analysis

PNACC- Plan Nacional de Adaptación al Cambio Climático

RCM- Regional climate models

RCP - Representative Concentration Pathways

SRES - Special Report on Emissions Scenarios

TCI- Tourism Climate Index

UN – United Nations

UNEP - United Nations Environment Program

UNWTO – United Nations World Tourism Organization

WEF - World Economic Forum

WGMS - World Glacier Monitoring Service

WMO - World Meteorological Organization

Summary

Climate is one of the main resources for attracting tourism. Knowing how it evolves, as well as how tourists behave in the face of different climatic and meteorological conditions is fundamental to finding and projecting the development of a fundamental economic sector in many countries and communities. Climate change and its adverse effects are currently one of the most worrying events for all humanity, given its global nature. Although there is still much to investigate about it, the negative effects on the territory and the ecosystems are already a measurable fact.

The negative consequences of climate change are not reduced to most direct effects, such as rising temperatures, but also extend to socio-economic activities. So much so that in recent years climate change has emerged on the international scene as a new area of concern for the tourism sector, among others, as climate is the main resource around which many tourist activities are generated. It is important to emphasize the significance of tourism activities in the Pyrenees, especially those linked to winter sports. A clear example is the socioeconomic impact of the dynamic effect of the snow sector on the region is the increase in income and generation of employment. However, it is also one of the tourist sectors most vulnerable to climate change, as specific conditions are required to enable the sport to be practiced and therefore, it is clearly affected by rising temperatures, lower water availability or a shorter duration of the snow cover, making the Pyrenees a highly vulnerable place with respect to the impact of climate change.

The structure and chapters of this thesis follow a strongly unified and coherent order. In the first place, the introductory chapter sets out a theoretical framework and background describing the importance of climate in tourism, climate change from the point of view of the intergovernmental panel on climate change, and how this can interfere with the patterns of tourist influx and the development of ski tourism in Spain. The second chapter presents the hypothesis, the main objective and the specific objectives of this thesis. Next, the central chapter presents the results structured as follows: A first chapter describing the current status of the issue and in which a bibliographical review has been carried out worldwide. The objective was progressing in the study of climate change on snow tourism in the main mountain ranges of the world. In addition, this chapter identifies the different methodologies of study, gaps or aspects that have not yet been studied, and finally serves to raise the hypothesis of original work. The area of analysis of this first part is on a world scale.

Once the main lines of research in the geographical area of this thesis - the Pyrenees - were identified, it was essential to know the present and past situation in the meteorological and nivological conditions. To this end, the second chapter of the thesis analyzes the trends in the snow and climatic conditions that most affect skiing. The trends are analyzed for a study period from 1960-2006. In order to find out future impacts the past and present of the situation must be established. In this second section of the study, the area of analysis is a large region, the Central Pyrenees comprising the Spanish side of the Pyrenees in Aragon, Catalonia and Andorra.

The 3rd chapter containing the results analyzes the influx of skiers to the ski resorts over 11 ski seasons, as well as the influence of weather conditions and the percentage of open tracks on tourist demand. This chapter analyzes the duration of the season, the days and the reasons for closing ski runs or ski stations, and the concentration of demand by month and holidays. A second part of this chapter analyzes the relationship between the number of skiers and the weather, as well as the link between the number of skiers and the percentage of open runs. In this case the scale of work is reduced and focuses on 3 of the ski resorts in the Aragonese Pyrenees.

Chapter 4th is based on a series of surveys conducted by personal and online interviews with the objective of unveiling the attitude of skiers to face various snow and climatic conditions. Once again, the study area comprises the entire Central Pyrenees. In this chapter, a qualitative analysis of the weather conditions preferred by tourists, as well as the elements of the climate and snow that influencing the decision to go skiing are analyzed. A second part analyzes the perception skiers have on climate change and their possible actions to take if snow conditions will deteriorate.

Finally, the 5th chapter of results analyzes how climate change will affect the number of ski days in two ski resorts in the Central Pyrenees, Formigal (Huesca) and Arcalís (Andorra), taking into account the spatial complexity of each resort (topography and elevation gradients) and the effectiveness of artificial snow to tackle the projected changes in climate on snow conditions.

The results chapters span from an exploratory analysis of the worldwide to a small scale analysis based on field methods. In the middle of the two extremes, the thesis provides a regional work scale, confined to the Central Pyrenees. The variety of the spatial scales included allows a rich but complex territorial reality to be depicted, as far as ski tourism is concerned. Within the earth sciences, regional geographical analysis is a scale of work that requires a holistic, systemic and above all integrative approach. This gives information on the territorial reality and is a useful tool for decision-making in the field of land use planning and the environment.

Finally, the thesis concludes with an overall assessment and general conclusions, by discussing the main findings and methodologies used, as well as any improvements or extension to the research. This chapter draws together the general conclusions of the thesis.

The following doctoral thesis entitled "*Effects of meteorological variability and climate change on ski tourism in the Spanish Central Pyrenees and Andorra: analysis of trends and future scenarios*" was carried out under the auspices of the doctorate program in Environment at the University of San Jorge and the Pyrenean Institute of Ecology (Consejo Superior de Investigaciones Científicas). The mode of presentation is a compendium of scientific articles that have been published or submitted in indexed journals. Throughout its trajectory it was aimed to cover the most relevant aspects of the climate and skiing in the Pyrenees as seen from different scales and methodologies of work. As the doctoral thesis progressed, the widest possible dissemination was given to the results obtained. We have published in scientific journals, participated in national and international congresses, as well as collaborating in specific European projects related to the subject matter.

Resumen

El clima es uno de los principales factores determinantes para el turismo. Saber cómo evoluciona, así como se comportan los turistas frente a las diferentes condiciones climáticas y meteorológicas, es fundamental para encontrar y proyectar el desarrollo sostenible de un sector económico fundamental en muchos países y comunidades. El cambio climático y sus efectos adversos son actualmente uno de los eventos más preocupantes para toda la humanidad, dada su naturaleza global. A pesar de las incertidumbres que aún existen sobre su evolución cronológica y características regionales, los efectos negativos sobre el territorio y los ecosistemas ya son un hecho mensurable. Las consecuencias negativas del cambio climático no se reducen a efectos directos, como el aumento de las temperaturas, o alteración de las dinámicas naturales sino que también se extienden a las actividades socioeconómicas. Tanto es así que en los últimos años el cambio climático ha emergido en la escena internacional como una nueva área de preocupación para el sector turístico, entre otros, ya que el clima es el principal recurso alrededor del cual se generan muchas actividades turísticas. Es importante destacar la importancia de las actividades turísticas en los Pirineos, especialmente aquellas relacionadas con los deportes de invierno. Un claro ejemplo es el impacto socioeconómico del efecto dinámico del sector de la nieve en la región es el aumento en los ingresos y la generación de empleo. Sin embargo, también es uno de los sectores turísticos más vulnerables al cambio climático, ya que se requieren condiciones específicas para poder practicarlo y, por lo tanto, se ve claramente afectado por el aumento de las temperaturas, la menor disponibilidad de agua o una menor duración de la capa de nieve, convirtiendo a los Pirineos en un lugar muy vulnerable con respecto al cambio climático.

La estructura y los capítulos de esta tesis siguen un orden unificado y coherente. En primer lugar, el capítulo introductorio establece un marco teórico y antecedente que describen la importancia del clima en el turismo, el cambio climático desde el punto de vista del panel intergubernamental sobre cambio climático, y cómo este puede interferir con los patrones de afluencia de turistas. Además se desarrolla un breve apunte sobre el desarrollo del turismo de esquí en España. El segundo capítulo presenta la hipótesis, el objetivo principal y los objetivos específicos de esta tesis. A continuación, el capítulo central presenta los resultados, estructurados de la siguiente manera: Un primer capítulo que describe el estado actual de la cuestión y en el que se ha llevado a cabo una revisión bibliográfica a nivel mundial con el objetivo de avanzar en el estudio del cambio climático en el turismo de nieve en las principales cadenas montañosas del mundo. Además, este capítulo identifica las diferentes metodologías de estudio, lagunas o aspectos que aún no se han estudiado, y finalmente sirve para plantear la hipótesis de este trabajo. El área de análisis de esta primera parte es a escala mundial.

Una vez identificadas las principales líneas de investigación, fue esencial conocer la situación actual y pasada en los Pirineos. Con este fin, el segundo capítulo de los resultados analiza las tendencias en la nieve y las condiciones climáticas que más afectan al esquí para un período de estudio de 1960-2006. En esta segunda sección de los resultados, el área de análisis es a nivel regional, el Pirineo Central que comprende la parte española en Aragón, Cataluña y Andorra.

El tercer capítulo de los resultados analiza la afluencia de esquiadores a las estaciones de esquí durante 11 temporadas, así como la influencia de las condiciones meteorológicas y el porcentaje de pistas abiertas en la demanda turística. Este capítulo analiza la duración de la temporada, los días y los motivos para cerrar las pistas de esquí y la concentración de la demanda por meses y días festivos. En este caso, la escala de trabajo se reduce y se centra en 3 de las estaciones de esquí del Pirineo aragonés.

El Capítulo 4 de los resultados se basa en una serie de encuestas realizadas a través de entrevistas personales y online con el objetivo de conocer la actitud de los esquiadores con diversas condiciones climáticas y de nieve. Una vez más, el área de estudio abarca todo el Pirineo Central. En este capítulo, se analiza cualitativamente las condiciones climáticas preferidas por los turistas, así como los elementos del clima y la nieve que influyen en la decisión de ir a esquiar. Una segunda parte analiza la percepción que tienen los esquiadores sobre el cambio climático y sus posibles respuestas si las condiciones de la nieve se deterioran.

Finalmente, el quinto capítulo de resultados analiza cómo el cambio climático afectará el número de días de esquí en dos estaciones del Pirineo Central, Formigal (Huesca) y Arcalís (Andorra). Se tiene en cuenta la complejidad espacial de cada estación (topografía y elevación gradientes) y la efectividad de la nieve artificial para hacer frente a los cambios proyectados en el clima y en las condiciones de nieve.

Los capítulos de resultados abarcan desde un análisis exploratorio a escala mundial hasta uno a pequeña escala basado en métodos de campo. En el medio de los dos extremos, la tesis proporciona una escala de trabajo regional, de los Pirineos Centrales. La variedad de las escalas espaciales incluidas permite representar una realidad territorial rica y compleja, en lo que respecta al turismo de esquí. Dentro de las ciencias de la tierra, el análisis geográfico regional es una escala de trabajo que requiere un enfoque holístico, sistémico y sobre todo integrador. Esto proporciona información sobre la realidad territorial y es una herramienta útil para la toma de decisiones en el campo de la planificación del uso del suelo, la ordenación del territorio y el medioambiente.

Finalmente, la tesis concluye con un capítulo de consideraciones finales y conclusiones generales, discutiendo los principales hallazgos y las metodologías utilizadas, así como cualquier mejora o extensión de la investigación. Teniendo en cuenta que en cada capítulo de resultados incluye la discusión, en este apartado se realiza un análisis más global, analizando especialmente los últimos avances y hallazgos.

Esta tesis doctoral titulada: "*Efectos de variabilidad meteorológica y el cambio climático en el turismo de esquí en el Pirineo Central español y Andorra: análisis de tendencias y escenarios de futuro*" se ha llevado a cabo bajo los auspicios del programa de doctorado en Medio Ambiente de la Universidad de San Jorge y el Instituto Pirineo de Ecología (CSIC). El modo de presentación es un compendio de artículos científicos que se han publicado o presentado en revistas indexadas. A lo largo del desarrollo de la misma se ha tratado de cubrir los aspectos más relevantes del clima y el esquí en los Pirineos. Además se ha dado la mayor difusión posible a los resultados obtenidos, publicando en revistas científicas, participando en congresos nacionales e internacionales, y colaborado en proyectos europeos específicos relacionados con el tema.

1. GENERAL INTRODUCTION

1.1 BACKGROUND

1.1.1 Climate as a factor of location for tourism.

Climate and weather have a profound influence on natural systems and human societies around the world. Weather can be defined as the state of the atmosphere at a specific time at a specific geographical location, with respect to the simultaneous occurrence of several meteorological variables (i.e. temperature, precipitation, wind, clouds, atmospheric pressure and others). Climate is commonly considered to be the weather averaged over a period of time, and effectively represents the conditions one would anticipated experiencing at a specific destination and time (Scott, Hall and Gössling, 2012). The intergovernmental Panel on Climate Change (IPCC, 2001) more rigorously defines climate as "the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years".

Tourism can be defined as movement in space undertaken by people in order to use other spaces as places of leisure. Is one of the largest global economic sectors and is a significant contributor to many national and local economies around the world. Demand for international tourism remained robust in 2016 despite challenges. International tourist arrivals grew by 3.9% reach a total of 1.235 million, according to the latest World Tourism Barometer (UNWTO, 2016). It is estimated that the global travel and tourism industry contributed 9.6% of global Gross Domestic Product [1](GDP) and 7.9% of worldwide employment. 2016 was the seventh consecutive year of sustained growth following the 2009 global economic and financial crisis. International tourism and travel is a vital contributor to the economy of many developing countries. Between 1995 and 2007, tourism and travel in emerging and developing markets grew at twice the rate of industrialized countries. Tourism and travel is a primary source of foreign exchange earnings in 46 out of 50 of the world's less-developed country. With international tourist arrivals projected to reach 1.6 billion by 2020, tourism will continue to have an important role in contributing to the UN Millennium Development Goals, particularly the alleviation of poverty in developing countries (UNWTO, 2016).

Economic activities are affected by influence climate and weather and, of these, outdoor ones, like tourism, are one of the most influenced. The elements of the climate have the greatest influence on tourism are temperature, number of sun hours, precipitation, wind, humidity, clearly (Gómez-Marín, 2005).

Every economic activity requires a territorial base, and so tourist activities need a geographical space. However, tourist activities are not distributed homogeneously in space; rather, certain activities are concentrated in specific points or areas. Numerous factors account for this pattern, in keeping with the varied and complex nature of tourism itself. Climate is one of the geophysical elements that make up geographical space, contributing to the environmental conditions that facilitate or hinder human settlement. Tourism, as a human activity, is also governed by these same imperatives. Therefore, climate is an

[1] PIB

important criterion for locating tourism centers, helping to determine how an area is to be used (Gómez-Marín, 2005).

Climate (sun hours, temperature, snow, wind, wind-chill, humidity, etc.) is often the main resource upon which a whole series of activities designed to satisfy tourist demand depend. However, climate merely complements other basic resources. In this sense in some cases the climate directly generates tourism such as ski tourism among other mountain sports, water sports such as windsurfing, or other wind sports such as sky diving. This type of sports depends directly on an element of the climate. Other types of sports tourism are simply climate-sensitive (such as hiking, rafting, golf, hunting, fishing and climbing). For example, wind speeds over 15 km/h were found to be detrimental for fishing or water skiing, whereas motor boating could be undertaken up to wind speeds of 50 km/h (Becken, 2010). Hence, climate-dependent activities are linked to a particular geographical space that has certain climatic characteristics. Due to the fact that some tourism activities are climate-dependent they can present a high seasonality as their practice can be done only during given, or only on during certain days. The increasingly, fear of seasonality is forcing centers and touristic consortium to make greater efforts to diversify, in an attempt to escape the ‘‘single cropping’’ practices of the past (Gómez-Marín, 2005).

On occasions, adverse weather conditions lead to, tourists to rethink their activities, abandoning outdoor in favor of indoor ones perhaps of a more cultural or social nature. Weather will also influence how enjoyable an experience is and therefore tourists' satisfaction is likely to be at least partly weather dependent. Finally, the safety of touristic activities can depend on the weather for example in relation to heat waves, extreme wind events or avalanches (Becken, 2010). As early as the 1970s, the Atmospheric Environment Service in Canada produced tourism and outdoor recreation handbooks that specified start and end dates for different kinds of activities and the climatic conditions that impact human comfort (Smith, 1990). The ski industry is a prime example of a weather dependent tourist activity: snow reliability is one of the top requirements for activity participation. Poor snow conditions have been linked to negative impacts on personal safety of tourists. During the poor snow conditions of the 1990/91 ski season in the Swiss and Austrian Alps, accident insurance claims by British skiers were almost double average levels, with approximately half listing accidents caused by exposed rocks and crowds on the ski runs (Smith, 1993). Cold winters are also linked to higher road accident rates, whereas warmer than usual winters reduce the likelihood of accidents (Koetse and Rietveld, 2009). So, knowledge of climate allows for general more sustainable strategies, and knowledge of weather conditions allows for appropriate tactics to enhance the comfort and pleasure for tourists.

The above discussion on tourism demand and weather impacts on tourist activities highlights that tourist destinations are exposed to natural climate variability and seasonality. This means that even under present-day conditions the profitability and viability of a business and destination is at least partly influenced by the climate. The exposure to climatic events will be exacerbated by climate change, although there are also opportunities due to potentially more favorable conditions in the future. It is therefore not surprising that increasing attention has been paid to how climate change might affect tourist destinations and how these can adapt to minimize risks and maximize opportunities (Becken and Hay, 2007; Becken, 2010).

1.1.2 Climate change and tourism

Climate system is a dynamic and open system therefore it is subject to variations. It is important to distinguish between climate change and climate variability. Climatic variability is defined as the oscillations of the climate around an average value that tends to maintain a permanent trajectory over time, although subject to continuous internal adjustments of the climatic system (Cuadrat and Pita, 2006). Instead, climate change is a statistically significant variation either in the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). According to the United Nations Framework Convention on Climate Change, climate change is defined as "a change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which adds to the natural variability of the climate observed during comparable periods of time".

The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental body established jointly by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). Was created in 1988 and that has provided policymakers to provide comprehensive assessments of the state of scientific, technical and socio-economic knowledge on climate change, its causes, potential impacts and response strategies.

Since the beginning of its work in 1988, the IPCC has prepared five multi-volume evaluation reports. The last Fifth Report of the IPCC published in 2014 declares that many of the changes observed since the 1950s have been unprecedented for millennia in recent decades. The IPCC is today confident with 95% certainty that human activity is currently the main cause of global warming. In addition, the Synthesis Report concludes that the greater the disruption of human activity to climate greater are the risks of serious, widespread and irreversible impacts on people and ecosystems, and the longer the changes in all components of the climate system.

Each of the last three decades has been successively warmer at the Earth's surface tan any preceding decade since 1850. The period from 1983 to 2012 was *likely*[2] the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible (*medium confidence*[2]). 2014 was the 38th consecutive year that average global temperature exceeded the twentieth-century average and the warmest year since systematic

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Very high confidence - at least 9 out 10 chance of being correct
High confidence- about 8 out of 10 chance
Medium confidence- about 5 out of 10 chance
Low confidence- about 2 out of 10 chance
Very low confidence- less than 1 out of 10 chance
Virtually certain->99% probability of occurrence
Very likely->90% probability of occurrence
Likely->66% probability of occurrence
About as likely- as not 33-66% probability of occurrence
Unlikely->33% probability of occurrence
Very unlikely<10% probability of occurrence
Exceptionally unlikely<1% probability of occurrence

instrument records began in 1880 (WMO, 2015). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85°C (0.65°C to 1.06°C) over the period 1880 to 2012. Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are *extremely likely*[2] to have been the dominant cause of the observed warming since the mid-20th century.

Global climate models are currently the best tool available to study the processes that make up the state of the climate. For this reason, they are essential to derive the response of the climate to the perturbations induced by human activities. Consequently, the ability of models to project future climate change depends primarily on the knowledge of the processes that govern the climate system. In order to make predictions and simulations on climate change, the IPCC uses a series of climate change scenarios.

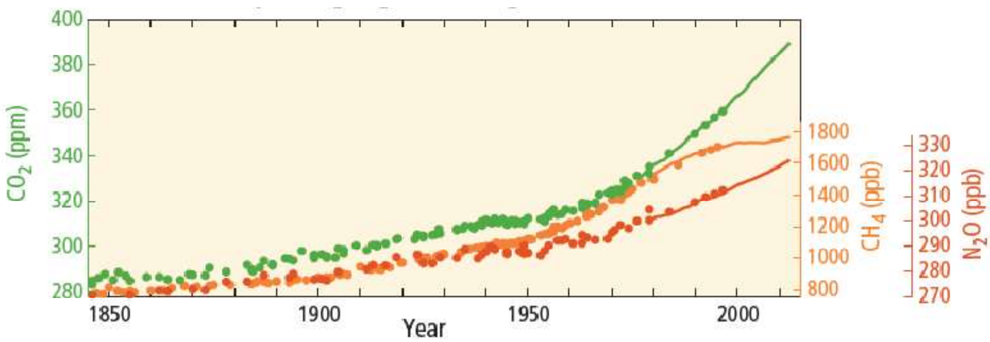

Figure 1: Globally average greenhouse gas concentrations. IPCC, 2014
CO_2 (Carbon dioxide); CH_4 (Methane); N_2O (Nitrous Oxide)

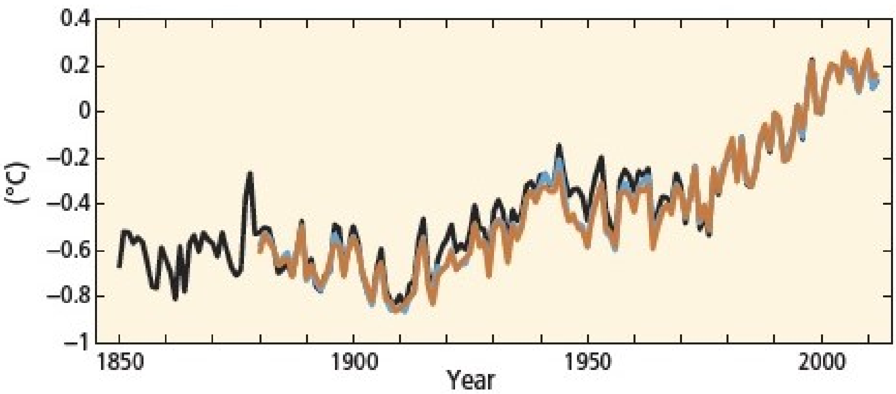

Figure 2: Globally average combined land and ocean surface temperature anomaly. IPCC, 2014

In the last IPCC report the standard set of scenarios used are called Representative Concentration Pathways (RCP). The RCPs represent the range of GHG emissions in the wider literature well; they include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming *likely*[2] below 2°C above pre-industrial temperatures. The RCPs cover a wider range than the scenarios from the Special Report on Emissions Scenarios (SRES) used in previous assessments. The main difference between the new RCPs and SRES is the inclusions of the effects of policies aimed at limiting climate change in the twentieth century or agreements aimed at mitigating emissions, against the emission scenarios used in the IPCC Fourth Assessment Report: Climate Change 2007 (AR4). In terms of overall forcing, RCP8.5 is broadly comparable to the SRES A2[3]/A1[3] scenario, RCP6.0 to B2[3] and RCP4.5 to B1[3]. For RCP2.6, there is no equivalent scenario in SRES. As a result, the differences in the magnitude of AR4 and AR5 climate projections are largely due to the inclusion of the wider range of emissions assessed.

According to the results obtained from the calculations with these scenarios of climate change, the global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs, and will *likely*[2] be in the range 0.3°C to 0.7°C (*medium confidence*[2]). This range assumes no major volcanic eruptions or changes in some natural sources (e.g., methane (CH_4) and nitrous oxide (N_2O), or unexpected changes in total solar irradiance. Future climate will depend on committed warming caused by past anthropogenic emissions, as well by the mid-21st century; the magnitude of the projected climate change is substantially affected by the choice of emissions scenarios. Climate change continues to diverge among the scenarios through to 2100 and beyond. The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is *likely*[2] to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5. The Arctic region will continue to warm more rapidly than the global mean.

		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range [c]	Mean	*Likely* range [c]
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

Figure 3: Global mean surface temperature change (2046-2065/2081-2100). IPCC, 2014

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***A1** scenario family describes a future world of very rapid economic growth, a global population that peaks mid-century and declines thereafter. (Corresponds to an overall concentration of CO^2 that would reach 850 ppm in the year 2100, 120% more than the current one).

***A2** scenario family describes a very heterogeneous world. The underlying the theme self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population.

***B1** scenario family describes a convergent world with a global population that peaks mid-century and declines thereafter, with rapid changes in economic structures toward a service and information economy, reductions in material intensity, and the introduction of resource-efficient technologies.

***B2** scenario family describes a world in which the emphasis on local solutions to economic, social and environmental sustainability. It is a world with a continuously increasing global population. (Corresponds to an overall concentration of CO^2 that would reach 850 about 760 ppm, approximately double the current one).

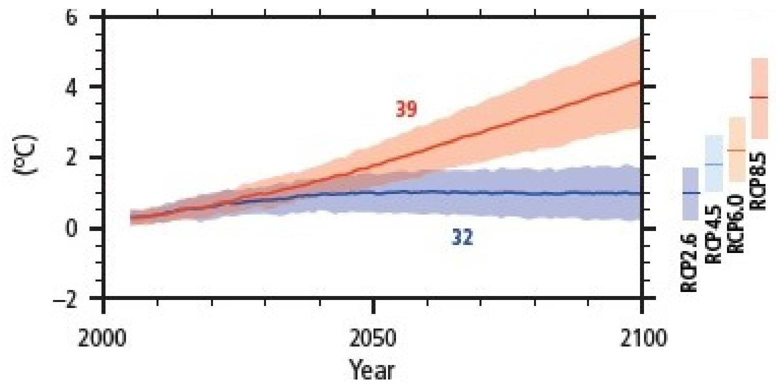


Figure 4: Global average surface temperature change (relative to 1986-2005) IPCC, 2014.

Changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are *likely*[2] to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will *likely*[2] decrease, while in many mid-latitude wet regions, mean precipitation will *likely*[2] increase under the RCP8.5 scenario). Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *verylikely*[2] become more intense and more frequent as global mean surface temperature increases.

There is *very high confidence*[2] that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century by 1.6 (0.8 to 2.4%) per decade for March and April, and 11.7% per decade for June, over the 1967 to 2012 period. There is *high confidence*[2] that permafrost temperatures have increased in most regions of the Northern Hemisphere since the early 1980s, with reductions in thickness and a real extent in some regions. The increase in permafrost temperatures has occurred in response to increased surface temperature and changing snow cover. The area of Northern Hemisphere spring snow cover is *likely*[2] to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the multi-model average (*medium confidence*[2]) (IPCC,2014). When the permafrost is exceeded the 0°C (approximately) begins its fusion, emitting carbon dioxide and methane gas to the atmosphere in its later decomposition. This emission supposes a greater greenhouse effect and therefore a higher temperature, which in turn accelerates the fusion and decomposition in the so-called feedback of the climate system with the carbon cycle (Schaefer, Zhang, Bruhwiler and Barret, 2011).

Tourism is currently considered one of the major economic sectors that are least prepared for climate change. Until few years ago, climate was considered a more or less stable characteristic of destinations. The climate change projections from the IPCC have led to a renewed interest in the relation between climate and the tourism sector. Although environmental change occurs at a global scale, regional and even local analysis are essential.

Climate change will result in both negative and indirectly or collaterally positive impacts for the tourism and travel sector and its impacts will vary substantially by geographic region and sector. There are four broad pathways by which climate change will affect the global tourism and travel sector second (UNWTO, 2009):

A) Direct climate impacts: Changes in the length and quality of climate-dependent tourism seasons (i.e. sun and sea or winter sports holidays) could have considerable implications for competitive relationships between destinations and intra-regional tourism flows. Other impacts will include increased infrastructure damage, additional emergency preparedness requirements, higher operating expenses (e.g. insurance, backup water and power systems, and evacuations), and business interruptions. Similarly, key cultural heritage assets that are also important attractions for tourists are also increasingly threatened by extreme climatic events and projected climate change.

B) Indirect environmental change impacts: Tourism is often based on a high quality natural environment. Changes in water availability, biodiversity loss, reduced landscape aesthetic, altered agricultural production (e.g. wine tourism), increased natural hazards, coastal erosion and inundation, damage to infrastructure and the increasing incidence of vector-borne diseases will all impact tourism to varying degrees. In contrast to the varied impacts of a changed climate on tourism, the indirect effects of climate induced environmental change are likely to be largely negative. Mountain, island, and coastal destinations are considered particularly sensitive to climate-induced environmental change, as are nature-based tourism market segments. Visitors may be deterred from visiting if the quality of the attractions decreases markedly.

C) Impacts of mitigation policies on tourism mobility: National or international policies to reduce GHG emissions will potentially impact tourism flows by causing an increase in transport costs and fostering environmental attitudes that lead tourists to change their travel patterns (e.g. shift transport mode or destination choices).

D) Indirect societal change impacts: The impacts of, and adapting to, climate change will have an economic cost. If not tackled, climate change may also threaten future economic growth and even the political stability of some nations. Any reduction of global GDP (Gross Domestic Product) due to climate change would have negative implications for anticipated future growth in tourism. Tourists are averse to political instability and social unrest, and there would be negative repercussions for tourism in the climate change security hotspots.

The place of tourism issue in the IPCC assessments has evolved since the First Assessment Report (FAR) in 1990. A number of major impacts that remain a focus of research today, including the impact of sea-level rise on coastal tourism and recreation, impacts on skiing, and the effect of climate change on biodiversity for tourism and recreation (e.g. fishing), were identified in the early First Assessment Report. Tourism also received substantial recognition in the FAR, a status it would not regain until the much improved content in AR5. Much of the early commentary on tourism and recreation in the IPCC reports was speculative and often not based on tourism specific research. This began to change as the number of publications related to the interactions of tourism and climate change more than doubled between 1996-2000 and 2001-2005 (Scott, Hall and Gössling, 2015).

Tourist response to marginal snow conditions and evolving regional ski tourism marketplaces remains largely unknown. Increased travel to see disappearing ecosystem types, or so-called "last chance tourism" (Lemelin, Dawson, Stewart, Maher and Lueck, 2010), is identified as a tourism phenomenon requiring greater investigation. Nurse et al, (2014) concluded that while extreme-weather events and degraded environmental conditions will significantly influence visitor's perception of destinations. Further uncertainties associated with differential responses of tourism markets and consistencies in the response of generational cohorts are discussed elsewhere in the literature (Scott et al 2015).

Impact	Implications for tourism
Warmer temperatures	Altered seasonality, heat stress for tourists, cooling costs, changes in plant-wildlife-insect populations and distribution, infectious disease ranges
Decreasing snow cover and shrinking glaciers	Lack of snow in winter sport destinations, increased snow-making costs, shorter winter sports seasons, aesthetics of landscape reduced
Increasing frequency and intensity of extreme storms	Risk for tourism facilities, increased insurance costs/loss of insurability, business interruption costs
Reduced precipitation and increased evaporation in some regions	Water shortages, competition over water between tourism and other sectors, desertification, increased wildfires threatening infrastructure and affecting demand
Increased frequency of heavy precipitation in some regions	Flooding damage to historic architectural and cultural assets, damage to tourism infrastructure, altered seasonality
Sea level rise	Coastal erosion, loss of beach area, higher costs to protect and maintain waterfronts
Sea surface temperatures rise	Increased coral bleaching and marine resource and aesthetics degradation in dive and snorkel destinations
Changes in terrestrial and marine biodiversity	Loss of natural attractions and species from destinations, higher risk of diseases in tropical-subtropical countries
More frequent and larger forest fires	Loss of natural attractions; increase of flooding risk; damage to tourism infrastructure
Soil changes (e.g., moisture levels, erosion and acidity)	Loss of archaeological assets and other natural resources, with impacts on destination attractions

Figure 5: Major climate change impacts and implications for tourism destinations. UNWTO. (2008)

Studies indicate that a shift of attractive climatic conditions for tourism towards higher latitudes and altitudes is very likely. As a result, the competitive position of some popular holiday areas are anticipated to decline (e.g., the Mediterranean coast in summer), whereas other areas (e.g., southern England or southern Canada) are expected to improve.

Uncertainties related to tourist´s climate preference and destination loyalty require attention if the implications for the geographic and seasonal redistribution of visitor flows are to be projected. There are well established vulnerabilities among winter sports destinations to projected declines in natural snowfall. Even with increased snow-making, contractions in the ski industry are very likely in the European Alps, Eastern and Western North America, Australia, and Japan, although projected impacts on destinations in these nations vary in magnitude and over different time horizons.

Direct impacts include changes in climate-related push-pull factors, changes in operating costs as a result of climate change and change to patterns of extreme weather events. In general, adequate climatic conditions are key for all types of tourism activities, ranging from conventional beach tourism to special interest segments, such as eco-, adventure-, and sport tourism. Furthermore, at some destinations, climate represents the primary attraction on which tourism is predicated. One of the most direct impacts of projected climate change on tourism will be the redistribution of climatic assets among tourism regions. Changes in the length and quality of climate-dependent tourism seasons (i.e., sun-and-sea or ski holidays) could have considerable implications for competitive relationships between destinations and therefore the profitability of tourism enterprises (UNWTO, 2009).

The international community is taking concerted action against climate change around a commonly agreed framework led by the United Nations. This UN framework has sought to establish a long term post-Kyoto road map with rapid deployment and targeted milestones. The tourism sector has an important place in that framework, given its global economic and social value, its role in sustainable development and its strong relationships with climate. To support this action the World Tourism Organization (UNWTO), jointly with the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO), with the support of the World Economic Forum (WEF) and the Swiss Government, convened the Second International Conference on Climate Change and Tourism, in Davos, Switzerland, (2007). This event, building on the results of the First International Conference organized on this topic in Djerba, Tunisia in 2003, gathered 450 participants from over 80 countries and 22 international organizations, private sector organizations and companies, research institutions, NGOs and the media, with the aim of responding in a timely and balanced way to climate change imperatives in the tourism sector. In preparation of this conference the organizers commissioned a report to provide an extensive review of current impacts and analyze options for possible actions.

The Conference agreed that:

Climate is a key resource for tourism and the sector is highly sensitive to the impacts of climate change and global warming, many elements of which are already being felt;

- Tourism, business and leisure will continue to be a vital component of the global economy, an important contributor to the Millennium Development Goals and an integral, positive element in our society;

- Given tourism's importance in the global challenges of climate change and poverty reduction, there is a need to urgently adopt a range of policies which encourages truly sustainable tourism that reflects a 'quadruple bottom line' of environmental, social, economic and climate responsiveness;

The tourism sector must rapidly respond to climate change, within the evolving UN framework and progressively reduce its Greenhouse Gas (GHG) contribution if it is to grow in a sustainable manner; this will require action to:

- Mitigate its GHG emissions, derived especially from transport and accommodation activities;
- Adapt tourism businesses and destinations to changing climate conditions;
- Apply existing and new technology to improve energy efficiency; and
- Secure financial resources to help poor regions and countries.

1.1.3 Impacts of climate change on mountain tourism

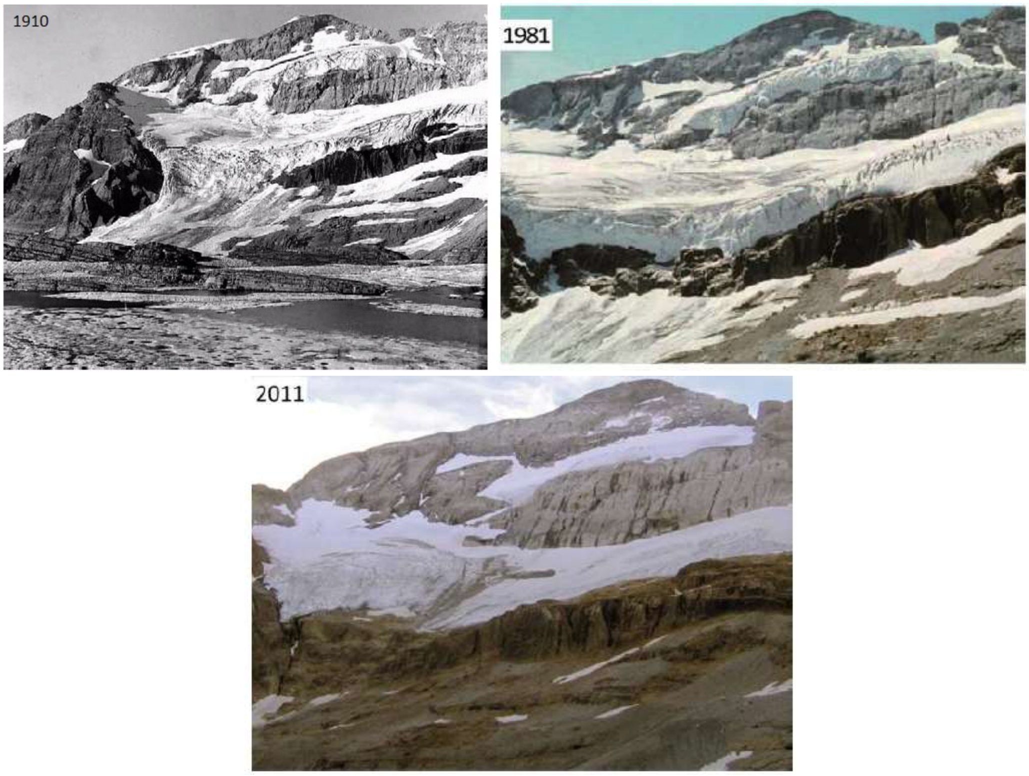
One of the places most vulnerable to climate change are mountain areas. In recent decades a significant increase in temperature has been detected in the majority of the mountain regions around the world. The warming has been generally accompanied by a shift toward earlier snowmelt and declining snow accumulation. This change in snowpack dynamics is a consequence of the great sensitivity of snow to air temperature increase, which causes a decreasing proportion of snowfall relative to rainfall, and an increase in available energy for snow melting (Scott, Hall and Gössling, 2012). 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, 2014). Although mountains differ considerably from one region to another, one common feature is the complexity of their topography. Orographic features include some of the sharpest gradients found in continental areas. Mountains in many parts of the world are susceptible to the impacts of a rapidly changing climate (Beniston, 2003).

Today the effects on mountain tourism are much more evident than in other types of tourism such as sun and beach and more complex adaptation measures. Mountain tourism can be affected by climate change in two main ways; the first due to the variation in the duration of tourist seasons, and secondly by the effect of climate change on ecosystems and elements such as fauna, flora or glaciers, causing the quality of the tourist product to fall with direct repercussions on the flows tourism and local economies.

The main impacts on mountain tourism are summarized in the following points:

- <u>Glacier retract:</u> Several studies have shown the increase in temperatures in these areas, the lower average thickness of snow and the greater temporary and territorial irregularity of snowfall. A measurable effect is the reduction of European glaciers that according to Beniston (2003), have lost 25% of their surface in 30 years.

(Beniston, 2003). The World Glacier Monitoring Service (WGMS, 2008) has recorded 19 consecutive years of regionally average retreat (negative mass balance). Mid-latitude mountain ranges such as the Himalayas, Alps, Rocky Mountains, and Andes, as well as isolated tropical summits such Kilimanjaro are showing some of the largest proportionate loss (Scott et al, 2012). The retreat of the glaciers brings associated consequences, Nyaupane and Chhetri (2009) identified a number of in Nepal avalanches, slope landslides directly related to the glacier shrinkage. This causes an increase of the water level in the lakes of glacial origin to the point of overflowing. Rising water levels in these lakes are potentially dangerous for communities living downstream and for the tourism industry in the area. Scott, McBoyle and Mills (2003) evidenced that the loss of glaciers reduce the very essence of Canada's natural parks, affecting tourism, in particular to the realization of tourist routes guided by snow and glaciers (snowcoach). In some glaciers in the Alps it is common to ski during off-winter seasons such as spring, summer and autumn, this type of tourism will also be affected by the loss of glacier mass, and some summer resorts have had to close (Elsasser and Bürki, 2002).



Photography 1: Monte Perdido glacier: Fotography Clemente-Álvarez and (1981-2011) López-Moreno et al, 2016.

- <u>Change in landscapes and biodiversity</u>: Perhaps less obvious changes in alpine landscapes will be the tremendous change in mountain ecosystems and natural hazards. Many alpine species have limited capacity to move to higher altitudes in response to warming temperatures, changed snow cover regimen and displacement by lowland species. In general, latitudinal and altitudinal changes are expected in the ecotones with possibility of reorganization of the species. The alpine habitat will raise altitudinal becoming increasingly fragmented (Scott, Jones, and Konopek, 2007; Omann, Stocker and Jäger, 2009) In addition, increasing tourist visits at specific times of the season could exacerbate existing pressures in some parks where visitors already pose ecological stress. Examples of these changes may be tourism related to the fall of forest foliage or bird watching. When the species are modified or the migratory patterns are changed, tourism in the area is also strongly affected.

- Sport tourism: Some tourist sports such as fishing may be altered by the movement of the species further north to find the temperatures appropriate to their habitat (Scott et al, 2003), or adventure sports such as kayaking, canoeing, canyoning that depend directly on the flow of mountain streams can be clearly affected by the modification of water regimes (Nyaupane and Chhetri, 2009).The impact of climate change on the snow-based sports tourism industry is potentially severe. The multi-billion Euro international winter sports industry has been repeatedly identified as at risk to global climate change due to the close linkage between economic performance and climate through the availability of natural snow and suitable climatic conditions to make snow. The key climate change impacts of interest to the winter sports industry relate to 'natural snow reliability' and also 'technical snow reliability' (i.e., cold temperatures to make snow). The latter is important in areas where snow-making is almost universal among ski areas and covers a high proportion of skiable terrain.

Despite the negative effects that climate change has on mountain tourism resources, several studies have shown that changes in tourist seasonality may have a positive effect in some cases. The warmer climate conditions that are projected to drastically reshape alpine landscapes will also provide opportunities for mountain destinations to extend the warm-weather tourism season (including activities like hiking and mountain biking) and provide comfortable climatic conditions as a retreat from the heat in urban centers and valley bottoms. Scott and Jones, (2006) showed that with increasing temperatures, visits to the Canadian natural parks would also increase. They predicted and increase of tourist of 6% by 2020s in a climate change scenario B2[3] and by 10% in a scenario of warmer climate change A1 above the average reference period 1961-1990. By 2050, an increase of visits of 10% in scenario B2[3] and of 36% in scenario A1 is expected. The increase is anticipated especially in the intermediate seasons of spring and autumn. Yu, Schwartz and Walsh (2009) for Alaska detected the elongation of the summer season in the last decades, beginning 10 days before with increased visits. However, the negative effects of climate change already evident in the area, such as the reduction of water levels in inland lakes, retreating glaciers, rising sea levels and impacts on ecosystems would have a negative impact on the visits for the future.

On the other hand, one of the most important characteristics of mountain tourism is the perception that visitors have of a natural space, for that reason the impact of climate change on the landscapes, the forests affected by fires, the loss of popular species, and the retreat of glaciers undoubtedly has a negative impact on social value and the number of visitors to protected areas around the world (Scott et al, 2003).

1.2 CLIMATE CHANGE AND TOURISM IN SPAIN AND CENTRAL PYRENEES

1.2.1 Climate change in Spain and Pyrenees

The tourism sector in Spain is highly important to its national economy. Spain has the highest number of nights spent by foreign visitors from all European countries (Hein, Metzger and Moreno, 2009). However, the tourism sector in Spain is also vulnerable to climate change. The way in which it can affect the country has been discussed in several analysis with diverse results. Most national assessments performed so far (De Castro, Martín-Vide and Alonso, 2005; Iglesias, Estrela and Gallart, 2005) relied on calculations obtained from broad-scale assessments from Atmosphere-Ocean coupled General Circulation Models (AOGCMs), published by the IPCC, which have low spatial resolution and a high degree of uncertainty (Garrido, Villaarts, López-Gunn and Rey, 2012).

In the scenarios known by the abbreviations A2[3] and B2[3] temperature increases in the Iberian Peninsula are projected to be essentially uniform throughout the 21st century, with an average trend of 1.2°C every 30 years in winter and 2°C every 30 years in summer for scenario A2[3], and of 1.1°C and 1.8°C respectively for scenario B2[3].

The trends of change in precipitation throughout the century are generally not uniform, with notable discrepancies between global models. However, they all coincide in a significant reduction in total annual rainfall, somewhat higher in scenario A2[3] than in scenario B2[3]. In response to this information gap, the Spanish Climate Change Office (*Oficina Española de Cambio Climático, OECC*), coordinator of the National Adaptation Plan to Climate Change (*Plan Nacional de Adaptación al Cambio Climático, PNACC*) issued in 2006, commissioned a regional assessment to be drafted on the likely impacts of change on water resources in Spain. The first output was publication of an assessment of the effects of CC on natural water resources (CEDEX, 2011), which represents the most up-to-date report on future climate scenarios on a regional scale for Spain (1 km^2resolution). According to this report, the mean annual temperature in Spain is expected to increase progressively throughout the 21st century, +0.065°C/year under A2[3] scenario and +0.048°C/year under scenario B2[3]. This means that by 2040 mean annual temperature in Spain could have increased by between +1.4 to +1.9°C. According to the CEDEX report, the mean annual precipitation is likely to decrease by up to -0.88 mm/year under the A2[3] scenario, and -0.18 mm/year under B2[3]. This implies that annual precipitation could decrease between 5% and 6% by 2040. However, there is still a high degree of uncertainty linked to future rainfall trends in Spain, since most regional models show prediction errors above 15% when estimating annual variations. The uncertainty in forecasts is even higher across seasons, with mean errors ranging from -33% to +30% (Moreno-Rodriguez, 2005).

Depending on the scenarios and magnitude of changes in temperatures and precipitation, some tourist destinations could benefit from climate change, thereby gaining competitiveness, while others will be less attractive in certain months or seasons. In general, the results show that, due to climate change, there will be an improvement in climatic conditions favoring tourism during spring and autumn, while in winter and summer the situation depends on the region and the type of activity, although in general destinations at higher latitudes and altitudes could be seen to benefit the most (Northern peninsular). On the other hand, large regions inland could experience significant decline in their climatic suitability, mainly due to the high temperatures. The impact on destinations and tourist flows will depend largely on their ability to adapt, as well as the flexibility of tourists to travel at times of the year outside summer months and other vacation periods of an institutional nature (Moreno, 2010).

According to Moreno (2010), the most relevant changes projected by the regional model for the last third of the 21st century in relation to the current climate can be summarized in the following points:

A) In the inland of the Iberian Peninsula the temperature will increase by about 5°C to 7°C in summer and 3°C to 4°C in winter in comparison with the current climate, in the A2[3] scenario. In scenario B2[3], the warming distribution is similar to that of A2[3], but generally 1°C less intense. In the periphery of the Peninsula and Balearic Islands, projected warming is in the order of 2°C lower than in the interior. In the Canary Islands it will be about 3°C lower than in the interior in summer and 2°C lower in winter.

B) Projected changes for cumulative precipitation are more spatially heterogeneous. There are slight increases in the north-west and slight decreases in the south-west in winter in both emission scenarios. There is a general decrease in rainfall in spring although somewhat higher in scenario A2[3] than B2[3]. Summer presents the maximum reduction in precipitation across the whole territory, except the Canary Islands. In autumn; A2[3] is projected to show a slight increase in the north-east and a decrease in the south-west, both of which are less intense in scenario B2[3].

C) The frequency of days with extreme maximum temperatures in the Iberian Peninsula tends to increase very significantly in spring and to a lesser extent also in autumn, whereas in the Balearic and Canary Islands no appreciable changes are observed, the same as with the other two seasons of the year across the territory. The frequency of days with extreme minimum temperatures in the Peninsula follows a decreasing trend (De Castro et al, 2005).

Regarding the impact of climate change by sector, different impacts are expected depending on the tourism sector analyzed. For example, the use of forests for recreational purposes can also be seriously affected by the risk of forest fires, as rivers and streams may be drying up or water quality deteriorating due to the presence, for example of algae. Coastal tourism could suffer from high temperatures and rising sea levels. Winter tourism will be affected by the reduction in the thickness of snow cover, as well as the loss of glacial masses (Moreno, 2010).

Pyrenees presents trends for temperatures and precipitation throughout the 20th century (Cuadrat et al, 2013; Perez-Zanón, Sigró and Ashcroft, 2016) Perez-Zanón et al, 2016 found an increase of 0.1°C per decade (1910-2013 period). A significant warming is found in all seasons except spring in minimum temperature and winter in maximum temperature. The annual regional precipitation shows a high inter-annual variability and a slightly negative non-significant trend of -0.6% per decade. Spring is the season that presents the greatest warming, with 0.9 degrees per decade for maximum temperature and 0.4°C degrees per decade for minimum temperature. Evaluating the same period for precipitation anomalies, trends in the annual, winter and summer series remain negative, while spring and autumn trends are positive although non-significant.

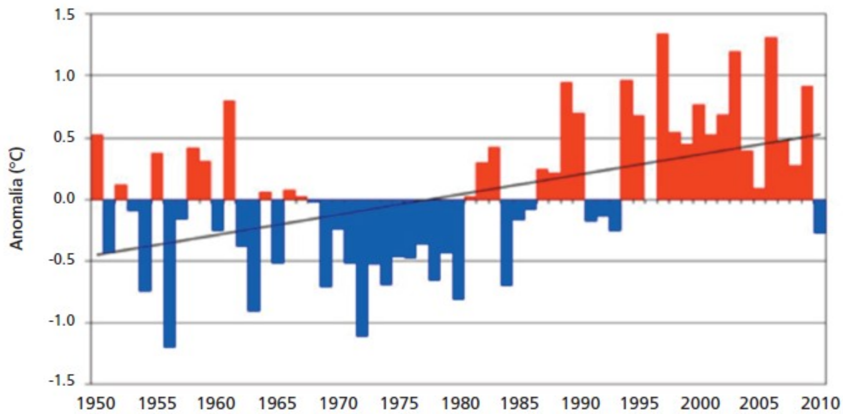


Figure 6: Anomaly of the annual average temperature compared to 1971-2000 period for the whole of the Pyrenees. Cuadrat et al, 2013.

Regional simulations with climate change scenarios can return a greater or lesser degree of uncertainty, since climate change can affect each region differently. In 2013, the downscaled scenarios for periods of 30 years up to 2100 for the variables of maximum temperature, minimum temperature and precipitation were performed for the Aragon region (Ribalaygua et al, 2013). The scenarios used were A2[3], A1B[4] and B1[3]. From the study it was generally deduced that the minimum and maximum temperatures for the region of Aragon will undergo a remarkable increase throughout the 21st century, with the rise in maximums being to some extent greater than the minimums. In both variables, the strongest rises occur in summer, followed by autumn, spring, and winter. The maximum temperature increases by mid-century (2040-2070) are expected to reach 3°C in summer and 2-2.5°C the

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The **A1** storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (**A1B**) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

rest of the year, while those of the minimum would increase by around 0.5°C less (2.5°C in summer and 1.5-2°C the rest of the year) in the A1B[4] scenario. As for precipitation, in the regionalization of scenario A1B[4], declines are expected throughout the twenty-first century, except in summer at the end of the century. In some seasons of the year a north-south gradient appears in the variation of the precipitation: in general, the north region and that referred to as Continental Sub-Mediterranean would undergo larger falls than the south zone (in which an increase in precipitation is predicted in autumn). In general, the central zone of Aragón would see slight variations in precipitation (Ribalaygua et al, 2013). While López-Moreno et al 2014 report that the climatic models indicate a generalized increase in temperature for the period 2021-2050 with respect to the control period (1970-2000). It is expected that the heating can oscillate between 1.5ºC in winter and spring, and almost 2.5 ºC in summer, with an annual average heating close to 1.8ºC. Climate models indicate a decrease in annual precipitation close to 10% with respect to the control period, with a greater decrease in summer (close to 18%) and lower in winter (less than 5%) for the A1B scenario.

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 at low elevation areas in the Pyrenees. At high altitudes, the expected change would be around -20% of the current snow cover. Lopez-Moreno, Goyette and Beniston, (2009) agree that the impact of climate change on Accumulated Snow Water Equivalent (ASWE)[5] is characterized by strong altitudinal gradients and horizontal spatial variability. Under B2[3] conditions, ASWE is likely to decrease by an average of 32% at 1500 m a.s.l.; this figure increases to 70% under scenario A2[3]. At 2000 m a.s.l., mean decreases in ASWE of 18% and 46% are simulated for the B2[3] and A2[3] scenarios, respectively. Areas above 2500 m a.s.l. are noticeably less affected by climate warming, with average decreases in ASWE of 8% and 22% according to B2[3] and A2[3], respectively.

Changes in precipitation and temperature could cause a decline in annual stream flow of between 13% and 23%, depending on the catchment in question. When the effect of increased forest cover in the basins is added to climate change effects, a decrease of up to 19% and 32% is found for the annual stream flow. The magnitude of hydrological change as a result of the assumed environmental change scenarios may lead to serious impacts on water management and the ecology of the studied region, as well as the availability of water in the Ebro basin (López-Moreno et al, 2014).

[5] Snow Water Equivalent (SWE) is a common snowpack measurement. It is the amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result of melted the entire snowpack instantaneously.

1.2.2 Ski tourism infrastructure in Spain and Andorra: development of ski tourism in Central Pyrenees.

In the Spanish mountains until the mid-twentieth century, in a similar way to other European mountain regions, the principal economic activity was farmland, and tourism was a relatively small phenomenon with few exceptions. In order to boost tourist activities and break with a regressive socioeconomic situation, the emigration of the population and the crisis of the primary sector, started in the early twentieth century in the sixties results in the built 29 alpine ski resorts (Lasanta, 2013). To legislative act (197/1963 of 28 December) regulating tourist centers and areas was passed in 1963 and with steals this enabled the construction of five alpine ski resorts in the region of Aragon and seven (five activates and two abandoned), in Catalonia (Lasanta, 2013).

Actually, 14 of these national ski stations are located in the Pyrenees (Candanchú, Astún, Formigal-Panticosa, Cerler, Baqueira Beret, Vallter 2000, Vall de Nuria, Masella, Tavascan, Espot Esquí, BoíTaüll, Port Ainé and La Molina) 3 are located in the Sistema Ibérico (Valdezcaray, Valdelinares and Javalambre), 4 in the Central System (La Pinilla, Sierra de Béjar-La Covatilla, Navacerrada and Valdesquí), 7 in Cantabria (Fuentes de invierno, Lunada, Leitariegos, Valgrande, San Isidro, Alto Campoo and La Manzaneda) and 1 in the Baetic mountains (Sierra Nevada), to which it is necessary to add a noticeable number of nordic ski resorts and other sport activities linked to the snow (ATUDEM, 2017).

The Spanish ski and snow tourism offers a total of 1.012 kilometers of ski slopes. Thus, we can see that the ski resorts are distributed among a large number of regions (Andalucía, Aragón, Asturias, Cantabria, Castilla-Leon, Cataluña, Madrid, Galicia, La Rioja and Navarra). The majority of the ski resorts are circumscribed in the modality of alpine ski [6]resorts.

According to ATUDEM (2017), the number of visitors to the ski resorts exceeds 5 million people and all of them enjoy an offer of accommodation of more than 217.000 places. Therefore, the data that document the flow of tourists to the mountain areas shows that the sector has assumed a determining economic importance.

On the other hand, 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 >8 million tourist visits every year (Andorra Turisme, 2017). Hence winter tourism is presented as one of the main income sources and the driving force of local development.

The first ski resort in Andorra was officially inaugurated in 1957, a ski lift of the Pas de la Casa that worked by the engine of a truck. At present, there are two large ski areas

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Skiing consists of descending a snowy mountain on supports in the form of an elongated board. Its practice goes back from ancient times although its geographical origin is not clear. It has had a great evolution during the centuries giving rise to very different modalities. The introduction of mechanical lifts implied a big push of this sport increasing noticeably the number of practitioners.

in Andorra: Grandvalira and Vallnord (The Vallnord ski area, located in the north of the Principality, has three ski resorts, Arcalís, Arinsal y Pal). Between them there are 115 lifts, with capacity to transfer more than 156.000 skiers per hour. 60 years after the installation of that first ski lift, Andorra already hosts major international winter sports events, such as the World Cup Alpine Skiing, World Cup Speed or World Cup Mountain Skiing (Pons et al, 2014).

In general, in the Pyrenees that the places suitable for the ski are in a situation close to the total exploitation and that the potential places for the enlargement of the skiing domains are scarce and most of them are limited by environmental regulations.

Figure 7: Ski stations in Spain. ATUDEM (2017)

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2. HYPOTHESIS AND OBJECTIVES

Based on the findings of other European and North American studies in other large mountain ranges, and in view of the impact of climate change on skiing, the hypothesis of this doctoral thesis posits that the inter-annual climatic variability and climate change can impact the tourism in the Pyrenees. This doctoral thesis is innovative since no such study of these characteristics using this methodology has been carried out for Spain .This would enable us to find the relationship between the mountain climate and tourism resources and to what extent they would be affected by climate change. The Aragonese Climate Change and Clean Energies Strategy adopted in 2009 includes tourism as one of the strategic sectors in Aragon for which there are still many open lines of research, among which this thesis is framed. Therefore, this project could serve as a basic tool to aid the public and private powers in the field of tourism and organization of the region in decision-making, based on a scientific analysis.

The main objective of this thesis is to find the relationship between the climate, snow conditions and weather with ski tourism in the central Spanish Pyrenees and Andorra. In order to improve knowledge about how this sector can adapt in a sustainable way to the impacts of climate change.

In addition, there are several specific objectives:

1. Study of the current status worldwide of climate change studies on winter tourism: Identification of study methodologies, gaps, and main lines of research.
2. Study of the trends of climatic and nivological variables affecting ski tourism during the second half of the 20th century in the Central Pyrenees.
3. Characterization of the demand for ski tourism in the Pyrenees as well as its relation with the climatic and nivological components and holiday schedules.
4. Analysis of the perception of skiers on various climatic conditions, climate change and likely attitude of skiers under deteriorating snow conditions for skiing.
5. Small scale impacts of climate change on ski conditions induced by elevation and topography, and the effectiveness of snowmaking to tackle projected climate change in the Pyrenees.

3. METHODOLOGIES, RESULTS AND DISCUSSIONS

En este capítulo se presenta la compilación de publicaciones científicas que se han llevado a cabo para esta tesis doctoral. De tal forma que cada una de estas publicaciones científicas se corresponde con un apartado de los resultados tal y como se expone a continuación:

3.1 Impacts of climate change on ski industry.

Título publicación: Impacts of climate change on ski industry
Título de la revista: Environmental Science and Policy
Año: 2014
Volumen: 44, 51-61
Autores: Gilaberte-Búrdalo, M., López-Martín, F., Pino-Otín, M.R., López-Moreno, J.I.
Factor de impacto y cuartil: 3.50; Q1
Estado: publicado

3.2 Assessment of ski condition reliability in the Spanish and Andorran Pyrenees for the second half of the 20th century.

Título publicación: Assessment of ski condition reliability in the Spanish and Andorran Pyrenees for the second half of the 20th century
Título de la revista: Applied Geography
Año: 2017
Volumen: 79, 127-142
Autores: Gilaberte-Búrdalo, M., López-Moreno, J.I., Morán-Tejeda, E., Jerez, S., Alonso-González, E., López-Martín, F., Pino-Otín, R.
Factor de impacto y cuartil: 2.56; Q1
Estado: publicado

3.3 Relationship of attendance at three ski stations in the Central Pyrenees with snow availability, holiday schedules, and weather conditions.

Título publicación: Relationship of attendance at three ski stations in the Central Pyrenees with snow availability, holiday schedules, and weather conditions.
Título de la revista: Tourism Management
Año: 2017
Volumen:
Autores: Gilaberte-Búrdalo, M., López-Moreno, J.I., López-Martín, F., Pons, M., Pino-Otín, R.
Factor de impacto y cuartil: 2,58; Q1
Estado: En revisión

3.4 Skier demand and behavioural adaptation to weather and climate change in Central Pyrenees

Título publicación: Skier demand and behavioural adaptation to weather and climate change in Central Pyrenees.
Título de la revista: Current Issues in Tourism
Año: 2017
Volumen:
Autores: Gilaberte-Búrdalo, M., López-Moreno, J.I., López-Martín, F., Pons, M., Pino-Otín, R.
Factor de impacto y cuartil: 1,23; Q1
Estado: En revisión

3.5 Local sensitivity of the snowpack to climate change in two ski resorts in Central Pyrenees.

Título publicación: Local sensitivity of the snowpack to climate change in two ski resorts in Central Pyrenees.
Título de la revista: Climate Research
Año: 2018
Volumen:
Autores: Pons, M., Gilaberte-Búrdalo, M., Trapero, L., Margalef, A., Pesado, C., López-Moreno, J.I.
Factor de impacto y cuartil: 1,57; Q1
Estado: En preparación

Para presentar los resultados de manera íntegra, tal y como están publicados los artículos en sus correspondientes revistas no se introducen modificaciones en los mismos, de tal manera que cada capítulo de resultados contiene su propia numeración de tablas y figuras, y su propio apartado de referencias.

3.1 IMPACTS OF CLIMATE CHANGE ON SKI INDUSTRY

Abstract

Ski industry has become one of the main economic activities for many mountain regions worldwide. However, the economic viability of this activity is highly dependent of the interannual variability of the snow and climatic conditions, and it is jeopardized by climate warming. In this study we reviewed the main scientific literature on the relationship between climate change and the ski feasibility under different climate change scenarios. In spite of the different methodologies and climate change scenarios used in the reviewed studies, their findings generally point to a significant impact of climate change on ski industry caused by a reduction in the natural availability of snow as well as a contraction in the duration of seasonal conditions suitable for ski. It emphasizes that the problem is real and should not be ignored in the study and management of tourism in mountain regions. However, there were significant differences in the impacts between different areas. These differences are mainly associated to the elevation of the ski resorts, their infrastructures for snowmaking and the various climate models, emission scenarios, time horizons and scales of analysis used. This review highlights the necessity from scientist to harmonize indicators and methodology thus allowing a better comparison of the results from different studies and increase the clarity of the conclusions transmitted to land managers and policy makers. Moreover, a better integration of the uncertainty in the model´s outputs, as well as the treatment applied to the snowpack in ski slopes is necessary to provide more accurate indications on how this sector will respond to climate change.

KEY WORDS: climate change; winter tourism; scenario, ski tourism; snowpack

3.1.1 Introduction

Climate change represents a global issue and its adverse effects constitute a risk to humanity. In spite of uncertainties about, chronological evolution and regional characteristics, the negative effects of climate change on ecosystems and socioeconomic activities are now a measurable fact.

Changes in snow and ice are one of the easiest impacts of climate change to be perceived since they respond rapidly to slight variations in precipitation and temperature (López-Moreno et al., 2008; Nesje and Dahl, 2000). Many studies have reported a decrease in snow thickness and duration in many mountain areas in the world. Thus, Laternser and Schneebeli (2003) and Marty (2008) reported years of unprecedented reduced snowfall after 1980. Less snowfall and snow accumulation was also detected in large parts of North

America (Harpold et al., 2012; the Italian Alps (Valt et al., 2005), Slovakia (Vojtek et al., 2003), northern Greece (Baltas, 2007), Spain (López-Moreno, 2005) and Himalayas (Dar et al., 2013). Changes in snowpack have been more marked at low altitudes (Scherrer et al., 2004).

For most mountain areas it is likely that there will be a decrease in the quantity of accumulated snow, a shortening of the snow cover period, and a decreased and earlier spring freshet (Barnett et al., 2005; Beniston et al., 2003).

In the last 25 years there has been strong growth in mountain tourism, which has become very economically important for many local communities and even at regional or country level. Thus, the economies of these communities are dependent on environmental conditions and factors affecting them, amongst which climate change is of major significance. From the whole range of tourist activities, the ski industry is the one with most economic and demographic influence in mountainous regions. Ski produces direct and indirect revenues related with the functioning of the ski resorts (Steiger, 2012). Even this industry has influences on demography development and the economic sector structure (Lasanta et al, 2007). Even this industry has influences on demography development and the structure of the economic sectors (Lasanta et al, 2007). For this reason, the ski industry is not considered as a simple business managed by private or public companies, but it is a key element to be considered by land managers. In many regions, policy makers and public administrations play a big role for improving the infrastructures for travelling and stay in the ski areas, for promoting the ski with publicity at different levels (schools, media, international fairs, etc) and, in some cases, subsidizing the development of ski resorts or its modernization, mainly for installing snow-making devices. For this reason, the high vulnerability of the ski industry to climate change is a complex, and conflictive issue for planning the future resources of mountain areas. The actions oscillate between an interest for promoting and supporting an activity that brings noticeable revenues and opportunities, and the risk to invest resources in a business of uncertain future and with high environmental impact (Koening and Abegg, 1997; Tranos and Davouli, 2014). In this debate, the evaluation and quantification of the impacts of climate change on ski industry in the various mountain regions of the world provide fundamental knowledge, but may also facilitate the development of adaptation or mitigation measures based on solid scientific studies that support decision-making.

Despite the great interest of the topic, the impacts of climate change on this sector started to receive some attention in the late eighties and nineties only (Breiling and Charamza, 1999; Galloway, 1988; Koening and Abegg, 1997; Koening 1998; McBoyle and Wall, 1992). However, the interest has noticeably increased in the last years at the same time of its economic and social importance.

In this paper, we conduct an extensive review of selected scientific literature on the impacts of climate change on ski industry. The main results reached in this field for different ski resorts located in Europe, North America, Asia and Oceania are summarized in the following section. They serve as basis to develop an overall discussion of the results, and to discuss about the major needs for further research in this topic in order to improve the accuracy and robustness of the conclusions and to enhance the usefulness of the results for the ski sector and policy makers.

The geographical areas encompassed by the review are shown in Figure 1, which includes an enlargement for the European area because of the high density of study locations in this continent.

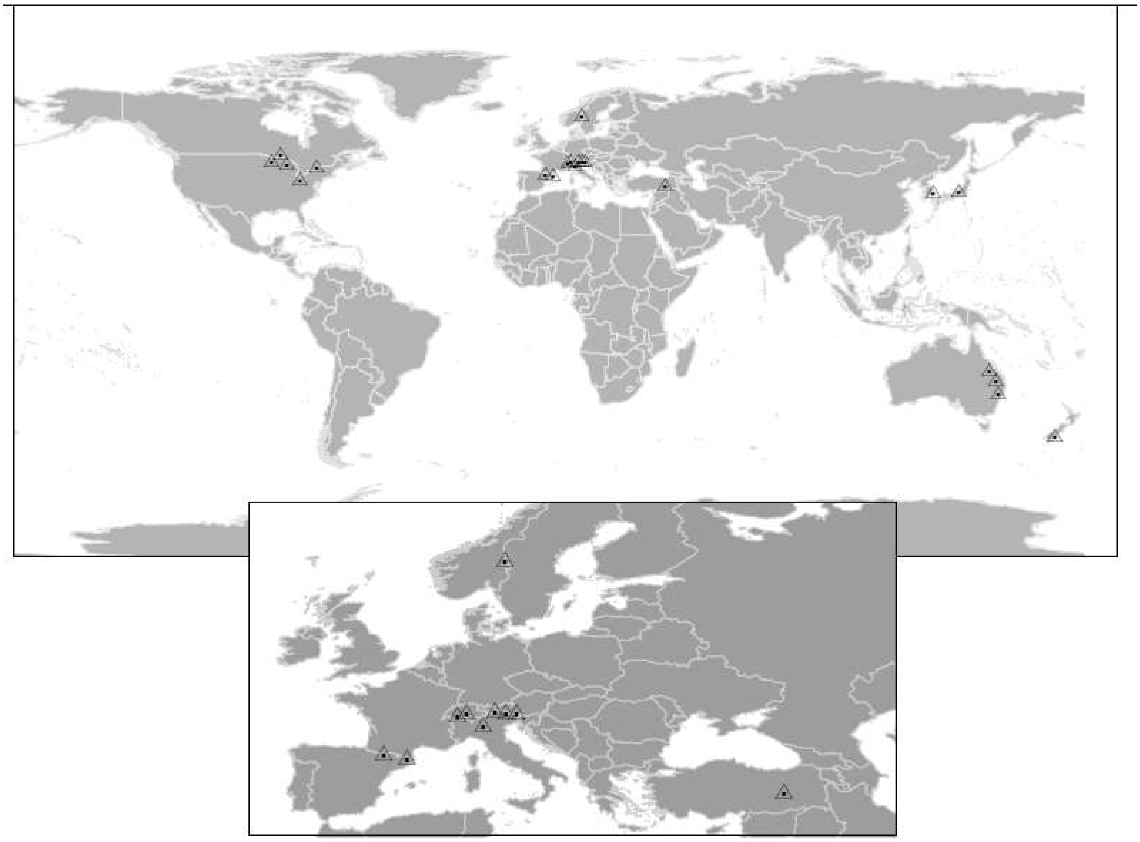

Figure 1: Studies location

3.1.2 Impacts of climate change on ski areas

Europe:

One of the first studies of the impacts of climate change on mountain tourism in Europe was carried out by Koenig and Abegg (1997). They investigated winter tourism in the Swiss Alps and highlighted the strong dependence of winter tourism on climate conditions, and on the availability of sufficient snow to support snow-based sports. The study stemmed from a period in the 1980s when the scarcity of snow over three consecutive years resulted in enormous economic losses in accommodation and transport sectors. Koenig and Abegg (1997) assessed what consequences a rise in temperature, would have on the future availability of adequate snow conditions. The results showed that a rise of approximately 0.3°C would result a rise on 300 m in the altitude of permanent snow in the Central Alps and by 500 m in the Pre-alpine region. Further a delay in the first snowfall of the season, and a reduction in the duration of snow cover by up to one month are expected. Under these climatic conditions the availability of snow will only be reliable in ski resorts located above 1200 m, which in the Swiss Alps includes 85% of the resorts. However, if the temperature rises by +2°C the snowline will move up to 1500 m, and under these conditions only 63% of the ski slopes will be feasible. Ski resorts at higher altitudes, including those of the Grisons canton and Valais, would have good skiing conditions even with a temperature rise of +2°C. In a further study in the same region, (Elsasser and Bürki, 2002) indicated that with an upward shift in the snowline to 1800 m a.s.l., only 44% of the ski runs and 2% of the ski lifts will be operable.

These impacts suggest that there will be a greater concentration of tourists in higher altitude areas, and consequent environmental problems related to increasing pressure on the water resources (supply), pollution, impacts on the flora and fauna and waste water disposal systems (Koenig and Abegg, 1997), and also problems derived from soil and landscape modification.

Abegg et al. (2007) confirmed this previous prognosis, and in the OECD (2006) (Organisation for Economic Co-operation and Development) study reported the consequences of warming of 1°, 2° and 4°C in the Swiss Alps. Their analysis indicate that 159 of a total of 164 Swiss ski resorts were viable, but this would drop to 142, 129 and 78, with a temperature increase by 1°, 2° and 4°C respectively. Despite this, Gonset (2013) stated that the ski industry is expected to be less affected in Switzerland than in the other European alpine countries.

Beniston et al. (2003) framed the sensitivity of the thickness and duration of snowpack in Switzerland with the simulated climate change projections from Regional Climate Models (RCMs) for the time slice 2071–2100. Results suggested a 90% reduction in snow quantity at an altitude of 1000 m, 40–60% reduction at 2000 m, and 30–40% reduction at 3000 m, all of which having negative consequences for ski tourism in the area. With respect to the duration of the snow season, for every 1°C average rise in winter temperature the snow cover would be reduced by an average of 15–20 days in the Alps. With a rise of 4°C the duration of snow cover would be reduced by about 50–60 days at altitudes of 2000–2500 m, and between 110–130 days at altitudes of approximately 1000 m. More recently, Uhlman et al. (2009) confirmed the uncertain future of Swiss ski resorts located at low altitudes, although they noted that there are marked local differences associated with the effect of slope and orientation on the sensitivity of the snow cover to climate change.

In the case of the Italian Alps, Mercalli et al. (2006, 2007) reported that a rise of 2°C or 4°C, would cause the snow line to rise by 300 and 600 m, respectively (EURAC, 2007). Moreover, it was reported that a rise in the current temperature of less than 1°C may cause serious loss of snow cover at altitudes < 1400 m, and that there would be a 35% reduction in the annual duration of the snow cover for every 1°C rise in temperature. Less extreme but noteworthy effects will occur at higher altitudes, where for every 1°C rise in temperature there will be an average loss in snow depth of 15% at approximately 1850 m, and 12% at 2300 m. Ski resorts in the Italian Alps are generally located at quite high altitudes. However, this does not preclude them from the impacts of climate change. Based on the assumption that for every 1°C rise in temperature the permanent snow line for skiing will rise by 150 m, out of the 167 ski resorts in Italy, 131 (located higher than 1650 m) will remain viable for winter sports. If temperature rise 2ºC , will be 88 resorts (higher than 1800 m) viable, and if the temperature rise 4ºC only 30 resorts (higher than 2100 m) will remain viable (EURAC, 2007).

The effect of climate change on the ski industry in Austria has been intensively analyzed in the last years in alpine region, Breiling and Charamza (1999) developed a statistical model including data on temperature, precipitation and snow cover, and concluded that at an altitude of 2000 m a temperature rise of up to 2°C with no change in precipitation would have no major consequences for the ski resorts, but at middle altitudes a rise of only 0.8°C would have serious consequences. Steiger and Mayer (2008) and Steiger (2010) noted the importance of artificial snowmaking to reduce the effects of climate change on sky resorts feasibility, although in some cases this will not be sufficient. Moreover, the potential number of days with optimal humidity and temperature conditions for making artificial snow will be reduced by approximately 33% if there is a temperature rise of +2°C. In a subsequent study, Steiger (2012) probed that the dependency on natural snow conditions has declined over recent years because of improved snowmaking techniques, although this has involved substantial increases in cost and investment, and ultimately this may directly affect the tourist affluence due to the rise of lift tickets price. Steiger and Abegg (2013) recently analyzed how climate change might affect winter tourism in Austria. This study was mainly based on three criteria: the 100-day rule (based on the assumption to be considered reliable ski resort needs a minimum of 100 days per season with a snowpack deeper than 30 cm 7 out of 10, winters Witmer, 1986); the ski season beginning on December 8; and the availability of sufficient snow during the Christmas holidays. The results of this study show that only 43% of a total of 228 ski areas met these criteria during the reference period (1961–1990). Based on the 100-day rule, increases of 1, 2 and 4°C would reduce total available areas for skiing and snowmaking by 81, 57 and 18 respectively. Under a +2°C temperature increase scenario more than 50% of the ski areas will have to increase snowmaking by 100–199%.

Moen and Fredman (2007) found that in Sweden during the period 1961–1990 the temperature increased by an average of 2°C, the precipitation remained stable, but the snow cover decreased by 8 cm depth. This resulted in a reduction of 5 days in the potential ski season, (measured as the number of days with at least 30 cm of snow depth, Elsasser and Bürki, 2002; Scott et al., 2003). The same study presents a detailed analysis for the region of Sälen (southwest Sweden). Under the A2 (about +5°C, and +45% precipitation) and B2 (about +2.5ºC, and +15% precipitation) regional climate change scenarios, showed the amount of snowfall would be reduced by 66% under scenario A2 and 44% under scenario B2.The duration of the ski season, which has been 162 days on average over recent years, will be reduced by 96 days under scenario A2 and 64 days under scenario B2.

López-Moreno et al. (2009) estimated that in the Pyrenees over the time period 2070–2100 there would be a decrease of 78% in the duration of snow cover at 1500 m under climate change scenario A2 (projected temperature increase in this study ranges from 2.4ºC to 4.1ºC with a mean change of 3.1ºC), and a decrease of 20% at 3000 m. Under climate change scenario B2 (temperature increase from 0.9ºC to 2.3ºC, with a mean change of 1.3ºC), they forecast a decrease of 44% in the duration of snow cover at 1500 m and 11% at 3000 m. Under scenario A2 they predicted a reduction of 70% in snow volume at 1500 m and an 11% reduction at 3000 m, whereas for B2 they predicted the reduction would be 32% at 1500 m and 5% at 3000 m.

More specifically, for the Aragonese Pyrenees (Spain) under climate change scenario A2 for the time horizon of 2040 it was concluded that the resorts will generally continue to be viable, but that low altitude areas will require artificial snowmaking because of the higher temperatures (Ribalaygua et al, 2013), especially during the month of March (Estudio sobre el sector de la nieve en Aragón, 2009). This report also indicated that the situation will worsen severely by the second half of the century. Thus, it was estimated that only resorts at an altitude of 1750–1800 m or higher has the snow viability guaranteed.
Pons et al. (2012) used the snow cover change scenarios developed by López-Moreno et al. (2009) to simulate skiability at three ski resorts (Arcalís, Pal-Arinsal and GrandValira) in Andorra at the end of the 21st century under scenarios B2 and A2. Two scenarios assumed an increase of +2°C and +4°C, respectively, and another two assumed the same temperature increase but incorporated artificial snowmaking. They found that based on natural snow availability only for the lowest areas of Pal-Arinsal would there be a contraction (30%) in the duration of the ski season with a temperature increase of +2°C, and with the introduction of artificial snowmaking the ski season length would be reduced by 25%. Under the +4ºC temperature increase scenario all three resorts would be seriously affected: the length of the season would be reduced by 95% at Pal-Arinsal, by 17% at GrandValira, and by 27% at Arcalís. The general conclusions of this study indicate that snowmaking will not be able to completely overcome the problems resulting from a temperature increase in the lower altitude skiing areas of Andorra (Pons et al., 2012).

North America:

In North America, studies on the impact of climate change on ski industry were initiated earlier than in other parts of the world. The first studies, carried out in Canada and the United States in the late 1980s (Lamothe and Périard, 1988; Lipski and McBoyle, 1991; McBoyle and Wall, 1987), projects reductions exceeding 50% in the skiable days. These projections overestimated the impact of climate change, primarily because they did not take account of mitigating measures including snowmaking technologies, which were now fully integrated into the operation of ski resorts (Scott, 2006). For Quebec, most recent studies indicate that the use of snowmaking has considerably reduces the vulnerability of these areas to climate change. Based on the IPCC climate change scenarios for 2020 and 2050, it was found that under scenario B2 (the lower temperature increase scenario) the reduction in snow depth will be 8% by 2020 (+ 1.4-1.6ºC) and 26% by 2050 (+ 1.9-2.3ºC), and will particularly occur during March, at the end of winter (Scott et al., 2007). For the higher temperature increase scenario (A1), the reduction will be about 29% by 2020 (+2.8 ºC) and 75% by 2050 (+7.4-7.9ºC). Under scenario B2 the ski season length will decline by 0–2% by the 2020s and by 4–7% in the 2050s, while for the A1 scenario the reduction will be 13–15% by the 2020s and approximately 30% by the 2050s. The need for artificial snowmaking under scenario B2 will increase by 15% by 2020 and 30% by 2050; for scenario A1 the increase will be 43% by 2020 and 131% by 2050.

In the Ontario region of Canada (specifically the Horseshoes ski resort) resorts are (in contrast to other areas) predicted to continue to be viable under a warmer climate, but assuming an increasing snowmaking capabilities, because with the current capabilities the average ski season is projected to decrease by 0–16% (B2-A2) in the 2020s, 7–32% (B2-A2) in the 2050s and 11–50% (B2-A2) in the 2080s, depending on the climate change scenario imposed (Scott et al., 2003).

In a study in the northeastern United States, Dawson et al. (2009) used the analogue approach to analyze the impact of climate change on the duration and permanence of the snowfall, and the effect of this on tourist demand for the time period 2040–2069. To represent an A1 climate change scenario they chose the 2001–2002 season, during which record temperatures of +4.4°C above long-term average were exceeded (based on the period 1960–1990). To represent a B1 climate change scenario they chose the winter 1998–1999 as the reference; during this winter the temperature was +2.7°C above the base period (1960–1990), and there was a 40% decrease in natural snow. The season was reduced by 5 days for the B1 climate change scenario and 15 days for the A1 scenario. The tourist demand will drop 11.6% in A1 scenario and 10.8% in the B1 scenario.

In a later study of the same area, Dawson and Scott (2013) used climate change scenarios A1 and B1 for the time frames 2010–2039, 2040–2069 and 2070–2099. They found that for the time period 2010–2039 only 55% (B1) and 54% (A1) of a total of 103 ski resorts would be viable (under the 100-day rule). The percentages were 54% (B1) and 40% (A1) for the period 2040–2069, and 45% (B1) and 29% (A1) for the period 2070–2099. Another parameter considered in this study was the ability to exceed 75% of probability to be operable during the economically important Christmas–New Year holiday period. The results showed for the 2010–2039 period only 44% (B1) and 44% (A1) of resorts would be operable over this period. The probabilities declined to 35% (B1) and 26% (A1) for the period 2040–2069, and 33% (B1) and 7% (A1) for the 2070–2099 periods. Based on the combination of the two parameters considered (100-day rule and 75% operational probability for the Christmas period), only 41 (A1) and 42 (B1) of a total of 103 ski resorts would be viable for the 2010–2039 period, 34 (A1) and 41(B1) for the 2040–2069 period, and 30 (A1) and 35 (B1) for the 2070–2099 period.

Asia:

There are relatively few studies on climate change and tourism for the Asian continent. Demiroglu (2000) analyzed 12 of the largest ski areas in Turkey based on climate change scenarios of +1°C (2025), +2°C (2050) and +4°C (2100), and the assumption of an upward movement of 150 m in the line of snow reliability for every 1°C rise in temperature. 6 of the 12 resorts are not operable with a +1°C temperature rise. With a +2°C rise only 2 resorts could operate, and under a +4°C increase none of the resorts analyzed will remain operable (Demiroglu, 2000).

Fukushima et al. (2002) developed a statistical model of snow conditions for Japan, to quantify how future climate change might affect tourist demand in the principal ski areas. First, they built a model for simulating snow depth based on the water and heat budgets. Afterwards, they statistically related the number of daily skiers with the simulated snow depth. They concluded that with a +3°C temperature increase and no change in precipitation there would be a reduction of 30% in the number of skiers visiting ski areas; exceptions were the Hokkaido region in the north, and high elevated areas on the main island. On the other hand, in the south of the country and in low elevation areas, the number of skiers could decrease by up to 50%.

For the Yongpyong resort in South Korea, Heo and Lee (2008) reported that since 1990 the snow cover depth and snowfall have decreased by 16% and 4%, respectively. Based on climate change scenario A1B for the 90-year period 2011–2090, they estimated that the ski season length will be reduced from the current 120 days to 105 days for the period 2010–2030, to 84 days for the period 2030–2060, and to 61 days for the period 2060–2090. Thus, between 2010 and 2090 the ski season length will decline by 42%.

Artificial snowmaking is an essential tool for the viability of all ski resorts in Korea, and particularly for the Yongpyong resort. Based on a temperature of –3°C and relative humidity of 60–80% being the ideal atmospheric conditions for artificial snowmaking (during the months of December to March), under climate change scenario A1B the optimal number of days for snowmaking in the period 2070–2090 will be reduced to 30 days from the 51 days for the 1970–2008 analysis period (Heo and Lee, 2008).

Oceania:

Australia and New Zealand are the only regions in the southern hemisphere from which there are scientific reports on the effect of climate change on ski resorts and ski tourism. Koenig (1998) analyzed the impacts of different regional climate scenarios on the Australian Alps. Based on a temperature increase of +0.3°C and the 60-day rule (natural snow-cover duration at least 60 days per season), all the ski resorts analyzed (9) will be viable in 2030 except for one. Under scenario (+1.3°C temperature increase), skiing will only be possible at one resort. Under the best-case scenario for 2070 (a temperature rise of +0.6ºC), six ski resorts will exist still; but in the worst-case scenario (+3.4ºC) no one of the resorts will remain viable.

In a more recent study of the Australian Alps, Pickering and Buckley (2010) analyzed the number of days with at least 1 cm of snow cover at 20 locations within the ski resorts, under a moderate climate change scenario of +1°C. By 2020 only seven of the 20 locations (35%) are expected to maintain at least 1 cm of natural snow cover for 70 days or more, two locations will maintain this cover for 60–70 days, and 11 locations will maintain this cover for < 60 days. The results of this study indicate that under a 1°C temperature rise scenario many ski resorts will not be viable with only natural snow conditions. The dependence on artificial snow will increase continuously, and it is possible that many resorts will not be able to meet the expense, and access the increased volume of water required. The most recent study in the southern hemisphere, conducted by Hendrikx et al. (2013), involved a comparative analysis of future impacts in Australia and New Zealand using in both places the same method of analysis. They considered three Global Climate Models and the mid-range emissions scenario A1. The results show that in New Zealand at lowest elevation (the most sensitive sites) the number of days with snow depths equal to or greater than 30 cm will be reduced from 125 currently to 111 days by 2040, and 68 days by 2090; in Australia it is currently 124 days and will reduce to 85 days by 2040 and 21 days by 2090 (this results are the mean values obtained from the three global climate models).

3.1.3 Overall assessment and conclusions

Most reviews of the impact of climate change on the ski industry have used climate change scenarios or fixed thresholds of warming in models for estimating future changes in snow conditions (especially snow depth and duration), and to assess how climate change might affect the viability of ski resorts in various mountain areas. Despite the relatively large number of studies addressing this issue in many different geographic areas, it is very difficult to compare the results because of the variety of methodologies used, the different parameters considered in assessing the viability of the ski industry under climate change conditions, and the various climate models, emission or warming scenarios, time horizons and scales of analysis used. Thus, among all the studies reviewed here (summarized in Table 1) few have been appropriate for direct comparison (Fig. 2). Adoption of common terminology, methods and indicators are necessary to facilitate comparison among different geographical areas, thus increasing the usefulness for decision makers of the results of studies in this field (Tranos and Davoudi, 2014). Thus, the regular consideration of indicators such as changes in the length of the ski season (considering different elevations and slope aspects within the specific ski resorts) and the reduction in number of skiers would help to compare climate change impacts on this economic sector. Figure 2 shows the decrease in the number of ski days and the percentage of ski resorts within a particular region that should be closed as a function of various scenarios of climate warming. The studies from which Figure 2 was derived, and the other studies reviewed, highlight how sensitive the ski industry is to increasing temperature, but also the large variability in skiability in response to similar warming rates. For example, changes in the number of ski days in response to climate warming at two resorts located in Andorra differed markedly (Fig. 2A; Pons et al., 2012). These differences can be largely explained by the average altitude of the resorts, or the latitude of the mountain regions involved. Thus, colder areas (because of high altitude or latitudinal location) are less affected by climate change, or may even benefit through spillover from lower-altitude resorts that are more vulnerable to the effects of climate change (Dawson and Scott, 2010; Koenig and Abegg, 1997; Scott et al., 2008).

In addition to the influential effect of increasing temperature on the ski industry, the evolution of future precipitation may partially balance or exacerbate the effect of climate warming on snowpack duration and accumulation (López-Moreno et al., 2012), and hence affect the skiability of a given resort or region. However, the projections for the future vary greatly, even over very short distances, and are subject to much greater uncertainty than for temperature (Dequé et al., 2007). Thus, assessment of the future of the ski industry should include the effect of changing precipitation together with warming effects, but fully account for uncertainty. In this way, decision makers would not considered specific results of climatic change, but with a range of scenarios ranked by the likelihood of their occurrence.

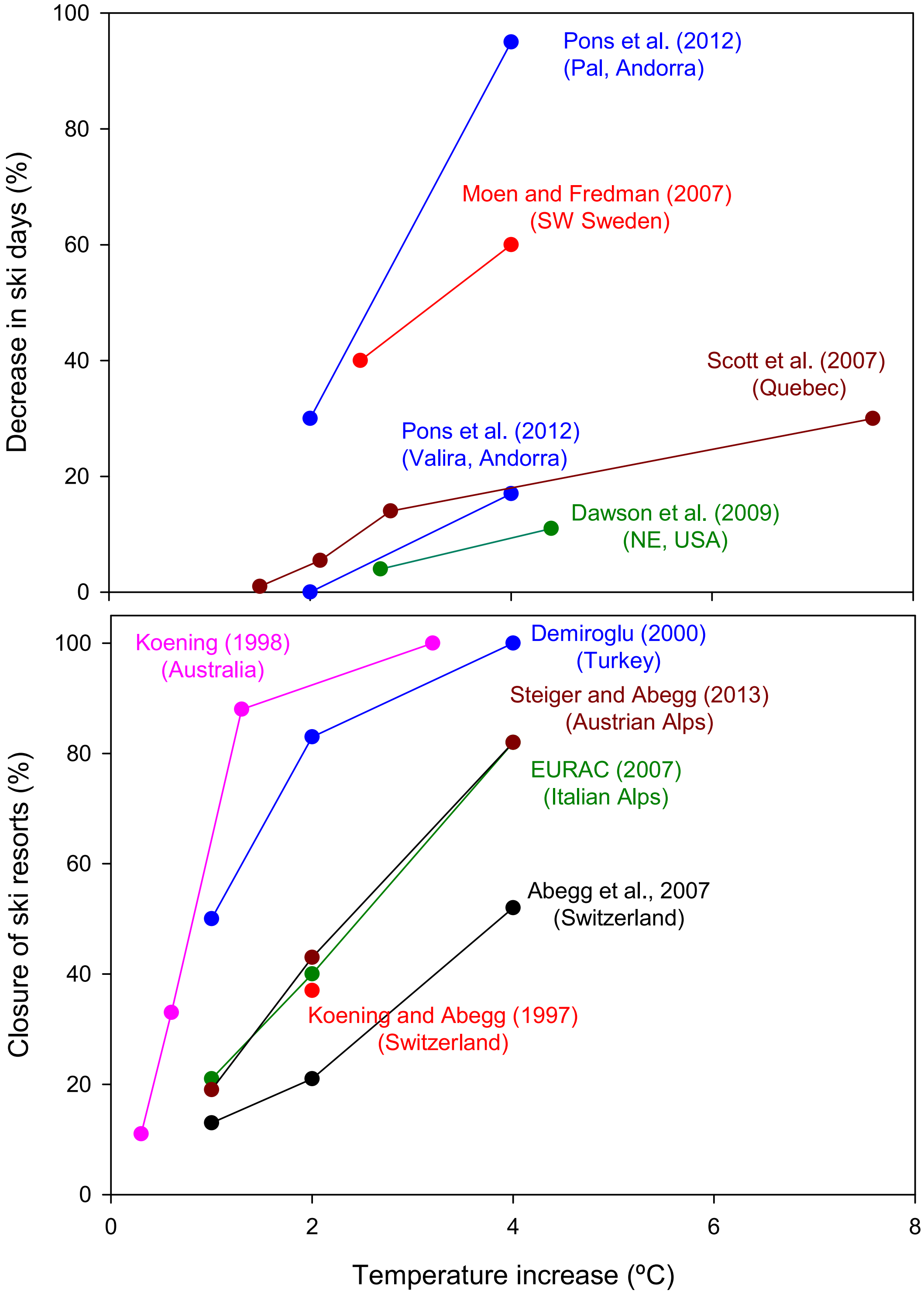

Figure 2: Reduction in the number of ski days and the percentage closure of ski resorts in various regions as a function of temperature increase.

Most of the reviewed studies assessed the viability of ski resorts under changing climate based on the simulated snowpack under natural conditions, and then used established criteria to assess the economic viability of the ski areas in determining the potential need for resort closure or a shorter ski season. These approaches are useful but require careful interpretation. Some of the established criteria for skiability, including the 30 cm threshold and a minimum annual operation time of 100 days (Abegg, 1996; Abegg et al., 2007; Dawson and Scott, 2007, 2010; Elsasser and Bürki, 2002; Koening and Abegg, 1997; Moen and Fredman, 2007; Pons et al., 2012; Scott et al., 2003; Scott et al., 2007; Steiger, 2010; Witmer, 1986), a 75% probability of being open during Christmas holidays (Dawson and Scott, 2013; Scott et al., 2008), or being operational on 8 December, the Christmas holidays and New Year (Steiger, 2013) cannot be systematically applied to all areas. There are other local factors to consider as the specific physical and technical characteristics of the resorts (e.g. roughness of the ski slopes and the location of the chair lifts), or the economic framework within which ski companies develop their activities (e.g. the number of employees, the price of water and energy, and the presence of public subsidies). Consequently, greater interaction between scientists and managers of ski areas is needed. Furthermore, many studies have only considered ski conditions based on the natural snowpack, whereas studies that have considered snowmaking in their simulations have highlighted this as a useful tool in reducing the impacts of climate change on ski businesses. However, various limitations associated with snowmaking have been reported. At lower altitudes at ski resorts there are fewer nights suitable for snowmaking, so more snowmaking guns are needed, and consequently there is more consumption of water and energy, and higher costs (Pickering and Buckley, 2010). Furthermore, increased water consumption for artificial snowmaking may generate conflict among mountain communities and various agricultural, urban residential, power generation and other industrial uses (Morrison and Pickering, 2013; Pickering and Buckley, 2010;). Consequently, ski companies and public bodies need to consider with caution the implementation of this adaptation tool (Hopkins, 2014; Vanham et al., 2009). In addition to snowmaking, the management of snow to improve its quality and duration on ski slopes is highly complex. The processes applied to the snow, including preparation of the ground, artificial snow production, redistribution and compaction, and modifications to snow roughness and its aerodynamic characteristics are encompassed in the term ‘snow crop’. These techniques markedly affect the density and thermal conductance of the snowpack, and the exchange of energy between the snow surface and the atmosphere (Fauve et al., 2002), as well as affect on the sensitivity of the snowpack to climate warming. However, no studies to date have considered physical transformations of the snowpack in developing future scenarios of ski conditions. We believe this aspect will need to be addressed in the near future to enable more accurate scenarios concerning the viability of ski resorts under changing climate to be provided to ski companies, government agencies and decision makers.

This review has highlighted evidence that climate change is a major threat to tourism through the closure of ski resorts in many mountain regions. However, despite the economic importance of skiing for many mountain regions, less snow does not necessarily imply the end of winter sports and tourism in these regions. Mountain areas are valuable landscapes and offer many attractions for tourists; these can offset, at least in part, the economic losses resulting from a worsening in the conditions for skiing. For example, the

2008–2009 winter season in the Black Forest was profitable from the point of view of tourism, despite the fact that this was the warmest period since 1961 (Endler and Matzarakis, 2011). In this regard, the development of activities complementary to ski tourism, such as snowmobiling, dog sleighing and ice fishing, can be developed, although these are also dependent on snow cover (Moen and Fredman, 2007). Year-round tourism not based on snow availability, such as hiking, kayaking and canyoning, have become important tourist options in mountain areas (Tranos and Davoudi, 2014). However, all are dependent on the availability water, and may be seriously jeopardized by climate change. Few studies have considered how climate change might affect these other types of tourism, so it will be of importance add the assessment of the effects of climate change on these other activities to the impacts on the ski industry. Overall assessment in this regard may provide robust tools to plan the management of tourism activities and devise strategies to minimize the negative effects of climate change in mountain communities.

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Country	Region	Climate change scenario used	Minimum altitude snow-reliable under CC	Snow pack duration	Snow depth	Loss of ski season	Others impacts	Study
Switzerland	Alps	+ 0,3ºC +2º C, no change p* (IPCC)	1200m 1500 m	-	-	-	63% resorts remain reliable	Koenig and Abegg (1997)
	Alps	+1 ºC +2 ºC +4 ºC	-	-	-	-	resorts remain reliable : +1 ºC (142 of 164) +2 ºC (129 of 164) +4 ºC (78 of 164)	Abegg et al, 2007
	Alps	A2 + 4ºC (2071-2100) + 1 (mm/day) precipitation (HIRHAM4; RCM)	-	- 50 days (2000m) ; -110 days (1000m)	-55%	-	Reduction snow fall -90% (1000m); - 45 -60%(2000m) ; -30-40% (3000m)	Beniston et al. (2003)
Italy	Alps	+1ºC ; +2ºC ; + 4ºC no change p	1650 m; 1800m ; 2100 m	+1 ºC = -35% (1400m); - 15% (1800m) ; - 12% 2300m	-	-	- 36 stations reliable; - 79 reliable stations ; - 137 rs	Mercalli et al. (2007); EURAC (2007)
Austria	Alps	+2ºC no change p	-	-	-	-	-	Breiling and Charamza (1999)
	Alps	A1 + 1ºC B1 + 2º C A2 +4º C	-	-	-	-	Ski reliable areas +1º -19% +2º - 43% + 4º - 82%	Steiger and Abegg (2013)

Country	Region	Climate change scenario used	Minimum altitude snow-reliable under CC	Snow pack duration	Snow depth	Loss of ski season	Others impacts	Study
Sweden	Sälen	RE-A2 +5ºC + 45%p RH-B2 +2.5ºC + 15% p (2070-2100)	-	-	-	-96 days (A2) -64 days (B2)	Reduction snow fall -66% (A2) -44% (B2)	Moen and Fredman (2007)
Spain/ France	Pyrenees	A2 +3,1ºC -1,6%p B2 +1,3ºC + 11%p (2070-2100)(HIRHAM; RCM)	-	A2 - 78%(1500m) -20%(3000m) B2 -44% (1500m) -11%(3000m)	A2 -70% (1500m); -11% (3000m) B2 - 32%(1500m) -5%(3000m)	-	-	López-Moreno et al. (2009)
Spain	Aragón Pyrenees	A2 + 5ºC -20%p B2 + 4ºC -10%p (2040-2100) (HadCM3 ; RCM)	1750-1800m	-	-	-	-	Estudio sector nieve Aragón (2009)
Andorra	Pyrenees	(HadCM3 ; RCM) B2+2º A2+4º	-	-	-	+ 2º -30% (Pal Arinsal) -3% (Arcalís) 0%(GrandValira) + 4º - 95% (Pal-Arinsal), - 27% (Arcalis) - 17% (GrandValira)	-	Pons et al. (2012)
Canada	Quebec	A1 CCSRNIES B2 NCARPCM (2020-2050)	-	-	A1 -29%(2020); -75%(2050) B2 -8%(2020) ; -26%(2050)	A1 -15% (2020); -30%(2050) B2 -2% (2020); -7% (2050)	snowmaking requirements A1 +43%(2020) + 131% (2050) B2 +15%(2020) + 30% (2050)	Scott et al. (2007)

Country	Region	Climate change scenario used	Minimum altitude snow-reliable under CC	Snow pack duration	Snow depth	Loss of ski season	Others impacts	Study
Canada	Quebec	A1 CCSRNIES B2 NCARPCM (2020-2050)	-	-	A1 -29%(2020); -75%(2050) B2 -8%(2020) ; -26%(2050)	A1 -15% (2020); -30%(2050) B2 -2% (2020); -7% (2050)	snowmaking requirements A1 +43%(2020) + 131% (2050) B2 +15%(2020) + 30% (2050)	Scott et al. (2007)
	Ontario	CGCM1-IS92a ; HadCM3-IS92a; CCSR-IS92a; CSIRO-A2 ; CGCM2-B2; HadCM3-B2 (2020-2050-2080)	-	-	-	CGCM1-IS92a -48% (2080); HadCM3-IS92a -37%(2080); CCSR-IS92a -45% (2080); CSIRO-A2 -50%(2080) HadCM3 B2 -11% (2080) CGCM2-B2 -19% (2080)	snowmaking requirements (2080) CGCM1-IS92a +380% ; HadCM3-IS92a + 312%; CCSR-IS92a +401% ; CSIRO-A2 +380% ; CGCM2-B2 +267% ; HadCM3-B2 +191%	Scott et al. (2003)
EEUU	Northeast	A1 +4,4ºC + 30%p B1 +2,7ºC +20%p (2040-2069)	-	-	-40%	A1 -11% (-15d) B1 -4% (-5d)	Drop in visits A1 -11,6% B1 -10,8%	Dawson et al. (2009)
	Northeast	A1 B1 (2010-2039; 2040-2069;2070-2099)	-	-	-	-	Snow reliable Ski areas under 100 d rules: 2010-2039 55%(B1), 54% (A1) 2040-2069 54%(B1), 40%(A1) 2070-2099 45%(B1) 29%(A1)	Dawson and Scott (2013)

Country	Region	Climate change scenario used	Minimum altitude snow-reliable under CC	Snow pack duration	Snow depth	Loss of ski season	Others impacts	Study
Turkey	General study	+1º (2025); +2º (2050) + 4º (2100)	2200m (2025); 2400 (2050); 2700m (2100)	-	-	-	Snow reliable nº ski areas -8 (2025) – 10 (2050) -12 (2100)	Demiroglu (2000)
Japan	General study	+3ºC no change p	-	-	-	-	Drop in visits -30% ; -50% in southern regions	Fukushima et al. (2002)
South Corea	Yongpyong resort	A1B (2011-2100)	-	-	-	-15days (2010-2030) -36days (2030-2060) -59days (2060-2090)	Suitable days for snowmaking -21days(50 days) 2008, 31 days 2060-2090)	Heo and Lee (2008)
Australia	Australian Alps	+0.3ºC + 1.3ºC (2030) +0.6ºC + 3.4ºC (2070)	-	-	-	-	Snow reliable ski areas +0.3ºC -1 (9) +1.3ºC -8 (9) (2030) +0.6ºC -3 (9) +3.4ºC -9 (9) (2070)	Koenig (1998)
	Australian Alps	+1ºC -8%p (2020)	-	35% locations with at least 70days >1cm	-60%	-		Pickering and Bukley (2010)
New Zealand		A1 (2030-2049) (2080-2099)	-	Days with snow depth ≥30 cm reduced from 125 days to 111 in 2040, and 85 to 2090	2040 – 0%-10% 2090 – 46%-76%	-	-	Hendrix et al. (2013)

3.2 ASSESSMENT OF SKI CONDITION RELIABILITY IN THE SPANISH AND ANDORRAN PYRENEES FOR THE SECOND HALF OF THE 20TH CENTURY

Abstract

In this study temporal trends of 14 climate and snow parameters related to ski conditions were analyzed for 11 ski stations located in the Central Pyrenees (Spain and Andorra). We also investigated whether there was a temporal association for the analyzed parameters, such that the occurrence in a particular year of good (or bad) climate or snow conditions as represented by one parameter was similarly reflected by the other parameters. The lack of reliable climate and snow measurements was overcome by the use of simulated climate data retrieved from a high resolution hindcast simulation available for the period 1960–2006. These data were also used as inputs for an energy and mass snow energy model to obtain snow series. The results showed trends in ski reliability parameters for the 1960–2006 period. The number of days having a snowpack deeper than 30 cm and 100 cm showed declines at low and mid altitudes. The start of the ski season appears progressively delayed for all stations, and the ski season shortened. The frequency of rainy days increased at 3 stations and decreased at 8, while the frequency of days having heavy snowfall increased at 8 stations and declined at 3. Days having potential for snowmaking declined at all stations. The number of days having a wind-chill < –20°C also decreased markedly, as overall did the number of days having a wind speed greater than 80th percentile. The main findings from the assessment of temporal associations between climate and snow parameters were positive correlations between snow depth and windy conditions. Seasons having a higher frequency of very cold days had a lower frequency of heavy snowfall and rainy days. Thus, the adverse effects on the ski industry of lesser snow availability may have been partially negated by the occurrence of fewer days of closure because of high winds, or other adverse meteorological factors.

KEYWORDS: climate and snow trends, ski reliability, MM5 data, Pyrenees, ski tourism, temporal concurrence.

3.2 1. Introduction

Tourism has emerged as one of the largest and fastest growing industries in the global economy (Eadington and Redman, 1991). For many countries, tourism has become an important source of business activity, income, employment, and demographic recovery in mountain areas (Lasanta, Laguna and Vicente-Serrano, 2007). For this reason, tourism is receiving increasing attention from regional politicians and land managers, and in some cases this has resulted in substantial subsidies for publicity and improvements to winter sport-related infrastructure (Gilaberte-Búrdalo, López-Martín, Pino-Otín and López-Moreno, 2014).

Among tourist activities, in recent decades skiing and other winter sports have become essential to the economy of mountain areas (Elsasser and Burki, 2002). However, these activities are highly dependent on climate and weather conditions, which can be limiting factors for ski tourism. The economic viability of this activity is highly dependent of the interannual variability of the snow, which is a crucial prerequisite for the skiing industry (Elsasser and Messerli, 2001; Pons et al., 2012; Scott, McBoyle and Mills, 2003; Steiger and Mayer, 2008). A lack of snow because of low precipitation or high temperatures is an immense challenge for winter sport destinations (Rixen et al., 2011), especially in the context of global warming, which is having major effects on many mountain areas worldwide. A reduction of the snowpack has been detected in recent decades across large parts of North America (Harpold et al., 2012), the Himalayas (Dar, Rashid, Romshoo and Mazari, 2014), the Mediterranean mountains (López-Moreno, Goyette, Vicente-Serrano and Beniston, 2011a), the Italian and Swiss alps (Marty, 2008; Valt, Cagnati, Crepaz and Marigo, 2005), the Pyrenees (López-Martín, Cabrera-Mollet and Cuadrat-Prats, 2007; López-Moreno, 2005), northern Greece (Baltas, 2007), low elevation areas in Slovakia (Vojtek, Fasko and Astný, 2003), and the Bulgarian mountains (Brown and Petkova, 2007). Witmer (1986) proposed the “100 day rule” to link skiing potential to snow availability, and this rule has frequently been applied in subsequent studies (Abegg, 1996; Abegg, Agrawala, Crick and De Montfalcon, 2007; Dawson and Scott, 2010; Elsasser and Bürki, 2002; Koening and Abegg, 1997; Moen and Fredman, 2007; Pons et al., 2012; Scott et al., 2003; 2007; Steiger, 2010). This rule postulates that a ski resort has natural ski reliability if there is sufficient snow cover (at least 30 cm) for 100 days annually between December and April in 7 of every 10 years. More recently, this indicator has been questioned because the 30-cm threshold is not equally applicable to all ski resorts given their different characteristics (Pons, López-Moreno, Rosas-Casals and Jover, 2015), and because the thickness and longevity of snow cover is normally estimated for natural snow, with no account taken of the production of artificial snow. The possibility of artificial snowmaking and manipulation of the snow on ski slopes (including grooming and alteration of the surface roughness) have been incorporated into recent vulnerability assessments (François, Morin, Lafayse and George-Marcelpoil, 2014; Pons et al., 2015; Steiger, 2010).

Compared with the number of studies that relate snow abundance and snowpack duration with skiability, almost no studies have considered the impacts of other climate variables that may be contributing to skiability at ski resorts. These variables, which may also influence the number of skiers, include the frequency of high winds and heavy snowfall days (probably the main cause of ski station closure), and rainy or extremely cold days. An interesting aspect of these issues is that for some specific ski locations the relationship of skiability to snow or climate parameters can be counterintuitive; for example, a snow-rich year may be associated with adverse weather conditions, or snow-poor years might be associated with anticyclone or temperature conditions that permit the production of artificial snow during the night. Various instances of this have occurred recently in the Spanish Pyrenees. During the Christmas period in 2014, sunny weather conditions attracted a large number of skiers despite the very poor snow conditions, which caused the closure of many of ski slopes. The opposite occurred during winter 2012–2013, when the snow depths reached record levels but skiing was problematic because of blocked roads, the occurrence of many rainy days, and the very high risk of avalanche. The relative absence of studies on this aspect of skiability has probably been exacerbated by the lack of reliable climatic or meteorological data available to perform sound analysis. Data scarcity is a significant problem with respect to the Pyrenees, and for this reason we used the outputs of a mesoscale model run at high resolution over the study area. This model is driven by reanalysis data to retrieve climate parameters related to skiability and develop a snow energy balance model ("Snobal"; Marks, Domingo, Susong, Link and Garen, 1999) that permitted us to simulate snow evolution at the studied ski stations.

The aims of the present study were: i) to assess the temporal evolution of climate and snow conditions related to ski tourism during the period 1960–2006 at 11 ski stations of the Central Pyrenees; and ii) to analyze correlations between snow and climate variables over this period to enable assessment of whether there was a temporal correlation.

3.2.2 Study area

3.2.2.1 Geographic and climate characteristics

The Pyrenees is a mountain range located in the northeast of the Iberian Peninsula, bounded by the Mediterranean Sea to the east and the Atlantic Ocean to the west. The Pyrenees extends over 425 km from west to east, and constitutes a natural border between Spain and France. The width (north–south) in the central part of the range is 150 km, and declines towards the west and east. Elevations (m .a.s.l.) vary from 500 m in some valley bottoms to 3404 m at the summit of Aneto Peak, with much of the area located above 1500 m (López-Moreno and García-Ruiz, 2004).

The climate is characterized by a progressive transition from Atlantic Ocean conditions in the west to Mediterranean conditions in the east. Thus, the Central Pyrenees has a mix of both characteristics, with strong continental features. The maximum precipitation occurs during winter in the western part, and during spring and autumn in the east (García-Ruiz, Berguería, López-Moreno, Lorente and Seeger, 2001). Much of the winter precipitation falls as snow from November to April, resulting in the development of a generally continuous snowpack above 1600–1700 m a.s.l. (López-Moreno and Nogués-Bravo, 2006).

The temperature is strongly influenced by topographic factors that result in an average rate of decline of 0.65°C per 100 m increase in elevation (Del Barrio, Creus, and Puigdefábregas, 1990). From December to April the 0°C isotherm is at approximately 1700 m a.s.l., above which the accumulated snow remains for long periods. Wind is an important climatic element in the Pyrenees that usually blows from the northwest; to a lesser extent from the north, west, and east (López-Moreno and Vicente-Serrano, 2006). When fronts arrive from the north and northwest, the moisture mostly discharges to the north and near the main divide of the Pyrenees (normally following the French–Spanish border), and as a consequence of the Foehn effect, dry and warm air masses arrive on the southern slopes of the Spanish Pyrenees. These results in there being marked differences between the Spanish and French mountain ranges in terms of snow accumulation, and this has direct effects on ski stations.

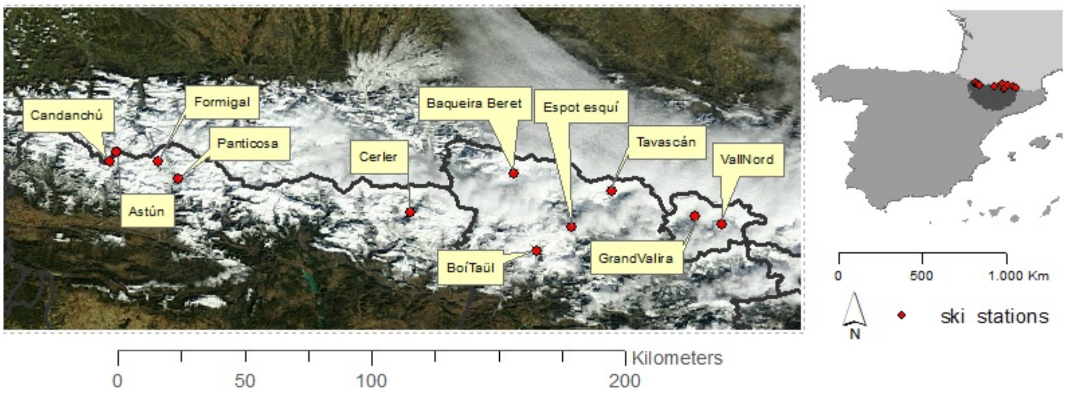
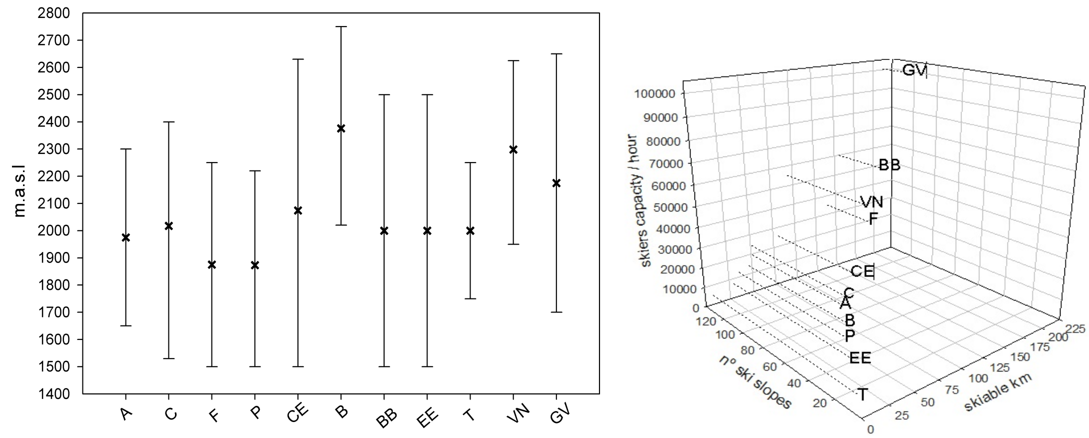


Figure 1: Study area and location of ski stations in the central Spanish Pyrenees and Andorra.

3.2.2.2 Ski stations characteristics

The 11 ski stations selected for this study are in the Central Pyrenees, 9 located in Spain and 2 in Andorra (Fig. 1). The lowest elevations for the ski slopes typically range from 1500 to 1700 m a.s.l. Only 30% of them have skiable areas higher than 2500 m, with 2800 m being the maximum. Figure 2 shows data for the study ski stations based on three criteria: length of ski slopes (km), the number of ski slopes, and the capacity to displace skiers per hour. The largest station is Grandvalira, which has 210 km of skiable area, the greatest number of ski slopes (118), and the greatest capacity (100.000 skiers per hour). Apart from four relatively large stations, the remainders have 45–79 km of ski slopes, and capacities of 15.000–25.000 skiers per hour. The three small stations the ski slopes range from 6 to 34 km in length, and the capacity ranges from 5000 to 13.000 skiers per hour.



A= Astún; C= Candanchú; F= Formigal; P= Panticosa; CE= Cerler; B= Boí Taüll
BB= Baqueira Beret; ES= Espot esquí; T= Tavascán; VN= Vallnord; GV= Grandvalira

Figure 2: Ski stations characteristics. A) Minimum, mean and maximum elevation. B) Number of ski slopes, total ski slope length, and capacity to displace skiers per hour.

3.2.3. Methods

3.2.3.1 Data

For each ski resort for the period 1960–2006 we calculated the number of days per season (from December to April) on which several climate or snow depth thresholds considered to define skiability were exceeded. The analysis involved the middle and lower elevations for each ski station, as these approximate the various levels of activity at the resort.

Because of a lack, or very short length, of climate observations for the ski stations, we used hourly data from a hindcast simulation performed with the PSU/NCAR MM5 mesoscale model (Grell, Dudhia and Stauffer, 1994) driven by the ERA40 reanalysis (Uppala et al., 2005) for its availability period, 1960-2002, and by ECMWF analysis data onward up to 2006. The simulation spans therefore the period 1960-2006 and the model spatial grid covers the study area with a horizontal resolution of 10 km. Time-series of the variables of interest at the specific locations of the ski stations were interpolated using distance-weighted averages from the nearest grid points. This simulated database has been used in previous studies for a variety of applications (Azorin-Molina et al., 2014, 2016 ab; Costas, Jerez, Trigo, Goble and rebêlo, 2012; González-Villanueva, Costas, Pérez-Arlucea, Jerez and Trigo, 2013; Hernández et al., 2015; Jerez et al., 2013; Jerez and Trigo, 2013; Lorente-Plazas et al., 2014), where its ability to reproduce regional circulations and local conditions has been widely demonstrated and technical details regarding model configuration can be found (e.g. Jerez et al., 2013; Lorente-Plazas et al., 2014). A further validation exercise will be presented in here.

To calculate the number of skiable days we used basic simulated weather data as inputs; these included temperature, precipitation, relative humidity, and wind speed. The temperature data were adjusted for the elevation of the various ski resorts by modifying the values to correspond to the grid-cell mean altitude seen by MM5, based on a lapse rate of 0.65°C 100 m^{-1}. We then computed and simulated derived climate and snow variables, including snow depth, wind-chill temperature, and snow making conditions, from the wet bulb temperature. From these temporal series we calculated the annual frequencies of 14 indicators of skiability, or limits to skiing activities (see Table 1 for a summary of the methods used). Snow depth was simulated using the "Snobal" snow energy and mass balance model (Marks et al., 1999), which is implemented in the Cold Regions Hydrological Model (CRHM) platform. This is a modular model that enables inclusion of hydrological processes for simulation of the hydrological cycle. It was devised to incorporate these and other algorithms, and to connect them for the purpose of simulating hydrological cycles in cold regions over small to medium sized basins (Pomeroy et al., 2007). This platform has been used in numerous studies to simulate the hydrological cycle components of cold environments (DeBeer and Pomeroy, 2010; Ellis, Pomeroy, Brown and Mc Donald, 2010; Zhou et al., 2014). The use of the model for ski stations at other sites in the Pyrenees has been fully described by López-Moreno et al. (2013, 2014). The inputs necessary to simulate snow depth include hourly data of temperature, precipitation, relative humidity, wind speed, and incoming solar radiation.

The thresholds considered for skiability (summarized in Table 1) included the following; (i) The number of days per season when the snow depth was greater than 30 cm and 100 cm at low and middle elevations, respectively. The 30 cm threshold has been used in many studies to represent the minimum thickness for safe skiing (Witmer, 1986). (ii) The start and end of the ski season at low and middle elevations. The start of the ski season was defined as the first day of the hydrological year (counted from 1 October) on which the snow depth was at least 30 cm for 15 consecutive days. The end of the ski season was the last day on which the snow thickness had been greater than 30 cm for 15 consecutive days. (iii) The number of rainy days per season, defined as the number of days per season on which more than > 10 mm of rainfall occurred during the hours 9:00–17:00 at the ski station. (iv) The number of days per season when heavy snowfall occurred at middle elevations, defined as the number of days per season on which at least 10 cm of snow accumulated during the hours 9:00–17:00 at the ski station. (v) The number of hours per season during which it was possible to produce artificial snow at low and middle elevations, defined by the occurrence of a threshold wet bulb temperature of –2°C. (vi) The number of days per season having a wind-chill of < –20°C at middle elevation. This was calculated based on temperature (T) and wind speed (Ws) using the formula $T = 13.12 + 0.6215 \times T - 11.37 \times Ws^{0.16} + 0.3965 \times T \times Ws^{0.16}$, as described by the Meteorological Service of Canada and the United States National Weather Service. (vii) The number of days per season on which the wind speed exceeded the long-term 80th percentile at middle elevation. As different stations have different thresholds of wind speed for continued operation, we used the percentile representative of high wind speed to enable comparison among ski stations.

Parameter analyzed	Threshold	Variable measured	Inputs	Data source	Software
No. of days with snow depth at low elevation	> 30 cm	Snow depth	Temperature Humidity Wind Precipitation	MM5	CRHM
No. of days with snow depth at low elevation	> 100 cm	Snow depth	Temperature Humidity Wind Precipitation	MM5	CRHM
No. of days with snow depth at middle elevation	> 30 cm	Snow depth	Temperature Humidity Wind Precipitation	MM5	CRHM
No. of days with snow depth at middle elevation	> 100 cm	Snow depth	Temperature Humidity Wind Precipitation	MM5	CRHM
Start of the ski season at low elevation	Julian day from 1 October	Snow depth	Temperature Humidity Wind Precipitation	MM5	
End of the ski season at low elevation	Julian day from 1 October	Snow depth	Temperature Humidity Wind Precipitation	MM5	
Start of the ski season at middle elevation	Julian day from 1 October	Snow depth	Temperature Humidity Wind Precipitation	MM5	
End of the snow season at middle elevation	Julian day from 1 October	Snow depth	Temperature Humidity Wind Precipitation	MM5	
No. of rainy days at low elevation	>10 mm	Rainfall	Temperature Humidity Wind Precipitation	MM5	
No. of snowfall days at middle elevation	> 10cm	Snow depth	Temperature Humidity Wind Precipitation	MM5	
No. of hours with possibility of snow-making at low elevation	<-2°C	Wet bulb temperature	Temperature Humidity Atmospheric pressure	MM5	
No. of hours with possibility of snow-making at middle elevation	<-2°C	Wet bulb temperature	Temperature Humidity Atmospheric pressure	MM5	
No. of days with excessive cold at middle elevation	<-20°C	Wind-chill	Temperature Wind	MM5	
No. of days with excessive wind	>80th percentile	Wind speed	Wind	MM5	

Table 1: Measured skiability thresholds.

To validate the simulated temperature, relative humidity, wind and precipitation data retrieved from the simulation, we used measured series from two stations located in the neighborhood of the Pyrenees (Pamplona, to the west, and Lleida, to the east); these meteorological stations are managed by the Spanish Meteorological Agency (AEMET) (Fig. 3). Thanks to a larger availability of long-term temperature and precipitation series we used 10 additional locations to validate the ability of MM5 to reproduce the average, the temporal correlation and the temporal trends of observed data (Table 2). These 10 stations cover a wider geographical extent, as well as a higher elevational range (from 8 to 1613 m a.s.l.). To validate the simulated snowpack we compared the snow depth measured at Izas and La Bonaigua (automatic weather stations) with the snow depth simulated at the same elevation at the nearby ski stations of Formigal and Baqueira, for the periods 1996–2005 and 1998–2005, respectively. Pearson´s r correlation coefficient and Willmott´s D were used as error estimators. The former measures the strength of the linear relationship between two quantitative variables. The latter reflects the magnitude to which observations are correctly estimated by the model; it is scaled using relative units (0–1) to indicate minimum and maximum accuracy (Ablan et al., 2011). It is not a correlation measure, but rather a measure of the degree to which the model is error-free.

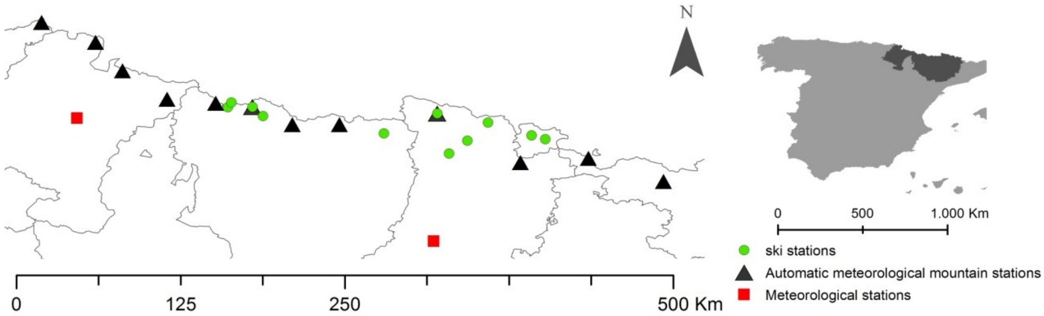


Figure 3: Weather stations used for validation. The green points indicate ski stations, the red box indicates meteorological stations of Spanish Meteorological Agency, and the black triangles indicate automatic meteorological mountain stations.

AMMS	ELEVATION (m.a.s.l)
Bielsa	1095
Candanchú	1613
Castelfollit de la Roca	296
Hondarribia	8
Izas	2056
La Bonaigua	2266
La Seo d´Urgell	692
Mata del Baztan	305
Orbaiceta	717
Puigcerda	1210
Torla	1053
Urzainqui	815

MS	ELEVATION (m.a.s.l)
LLeida	167
Pamplona	452

Table 2: Name and elevation of the validation stations. AMMS are the automatic meteorological mountain stations, MS are the meteorological stations of Spanish Meteorological Agency.

3.2.3.2 Statistical analysis

Linear regression was used to measure the magnitude of change in each of the 14 parameters during the study period, based on values for the first (1960) and last (2006) dates simulated in the linear fit. The statistical significance ($p < 0.05$) of the trends was estimated using the non-parametric Tau Kendall index test; this method (Kendall and Gibbons, 1990) measures the magnitude of association between two variables (time and the evolution of each variable).

We used principal component analysis (PCA) to analyze the entire set of climate and snow variables according to the homogeneity of their trends. In this analysis ski stations were the cases and the magnitude of the temporal linear trends were the input variables. PCA facilitates synthesis of a large number of interrelated variables into a few independent principal components that capture much of the variance in the original dataset (Hair, Anderson, Tatham and Black, 1998). It has been widely used to determine the temporal and spatial patterns of different climate variables (López-Moreno and Vicente-Serrano 2006; Peña, Arán, Cunillera and Amaro, 2011), and enables common features to be identified and specific local characteristics to be determined (Richman, 1986). We selected the two first components, which accounted for 90% of the variance. A correlation matrix was selected for the analysis because it provides a more efficient representation of the variance in the dataset. The PCA components were rotated to assess invariable spatial patterns; the rotation simplifies the spatial patterns of the studied variables (Barnston and Livezey 1987), and redistributes the final explained variance. The rotation procedure facilitates a clearer separation of components that maintain their orthogonality (Hair et al. 1998), and concentrates the loading for each PC onto the most influential variables. We used the Varimax rotation, which is the most widely used because it produces more stable and physically robust patterns (Richman, 1986).

3.2.4. Results

3.2.4. 1. Validation of MM5 outputs and simulated snow depth series

Figure 4 shows the observed climate values for the Lleida and Pamplona stations compared with the corresponding simulated MM5 data. The correlation coefficients (R) and Willmott´s (D) values for the observed climate data (average values for the snow season from December to April for the period 1960 to 2006) are also presented. The temperature was accurately simulated for both stations, with values of R and Willmott´s D > 0.87 in both cases. Precipitation was also accurately simulated for both stations, with values of R and D greater than 0.73 and 0.79 for the Lleida and Pamplona stations, respectively. Table 3 is consistent with the results from Lleida and Pamplona, with a reasonable good ability to reproduce the average values of temperature and precipitation (generally with a bias lower than 1ºC and 25% respectively), and also high R values, especially for temperature. Interestingly, Table 3 also informs that MM5 has a good capability to reproduce observed statistically significant ($p<0.05$) positive trends for temperature in the majority of the locations, and the negative trend (frequently with statistical significance, $p<0.05$) for precipitation. For wind speed the D values were very low (0.23–0.27) compared with the very high Pearson´s R value (0.83), indicating a systematic overestimation of 1.4 m s^{-1} in the MM5 simulations. However, we used a relative value (the 80th percentile) for classifying days as windy, and the wind data for snow simulation and calculation of the wind-chill factor were corrected using a factor equivalent to the calculated bias. Thus, for these parameters the Pearson`s coefficient exceeded the Willmott`s D value.

With respect to the relative humidity for the Lleida and Pamplona stations, the Willmott's D value was 0.37 and 0.43, respectively, and the Pearson´s R value was 0.43 in both cases.

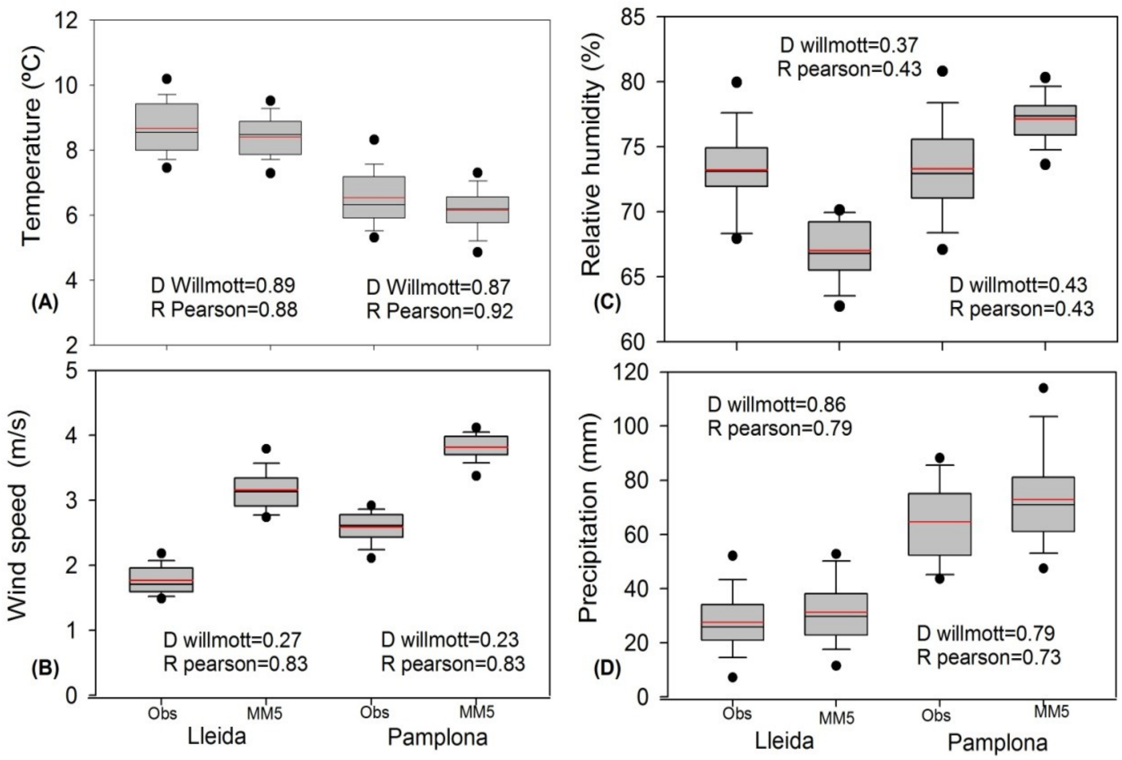


Figure 4: Validation of the variables temperature, relative humidity, wind speed, and precipitation for the period 1960–2006 for the Lleida and Pamplona stations, and the corresponding Willmott's D and Pearson R values. A: temperature; B: relative humidity; C: wind speed; D: precipitation. In each box the plots on the left correspond to the Lleida station and on the right to the Pamplona station. In each pair, the plot on the left represents the observed data and the plot on the right represents the simulated data (MM5). The red lines represent the average values for months January to April.

Nº	Elev	Bias (ºC)	D	r	Bias (%)	D	r	Tau_o	Tau_s	Tau_o	Tau_s
		Temp	Temp	Temp	Precip	Precip.	Precip	Temp	Temp	Precip	Precip
1	8	-1.1	0.73	0.62	14	0.88	0.58	0.21*	0.24*	-0.04	-0.06
2	305	0.34	0.91	0.62	27	0.78	0.61	0.29*	0.29*	-0.19*	-0.14
3	815	-0.63	0.82	0.63	54	0.64	0.66	0.25*	0.18	-0.21*	-0.14
4	717	-0.53	0.89	0.86	22	0.81	0.66	0.24*	0.20*	-0.24*	-0.20*
5	1613	-0.9	0.75	0.81	28	0.77	0.68	0.24*	0.33*	-0.16	-0.18
6	1053	-0.27	0.92	0.82	34	0.69	0.72	0.25*	0.34*	-0.15	-0.18
7	1095	-1	0.75	0.81	9	0.94	0.74	0.24*	0.32*	-0.11	-0.19
8	692	0.07	0.98	0.84	-21	0.82	0.69	0.19*	0.26*	-0.23*	-0.17
9	1210	-1.2	0.71	0.78	-17	0.85	0.62	0.18	0.23*	-0.19	-0.14
10	296	-0.94	0.74	0.81	8	0.95	0.66	0.14	0.21*	-0.27*	-0.24*

Table 3: Validation of winter temperature (Temp) and precipitation (Precip) series (1960-2006) in 10 locations distributed in the Pyrenees. D informs of the Willmott´s D value. r informs of the Pearson correlation. Tau_o and Tau_s inform about the Mann-Kendall´s Tau coefficient of the temporal series of observed and simulated (MM5) precipitation respectively. * informs of statistically significant trends ($p<0.05$).

1= Hondarribia; 2= Mata del Baztan; 3= Urzainqui; 4= Orbaizeta; 5= Candanchú; 6= Torla; 7= Bielsa; 8 = La Seo d`Urgell; 9 = Puigcerda; 10= Castelfollit de la Roca

Figure 5 shows the observed and simulated average monthly snow depth from December to April for the period 1996 to 2005. A snow depth simulation for Izas closely matched the observed data (Pearson´s r and Willmott´s D values were always > 0.70; the simulations for March were particularly accurate, with values > 0.90). For Baqueira, the simulated snow depth was accurate for all months except December and April, which can be explained by a larger error in simulation of the snow depth during 2005; for other years the simulations were much more accurate.

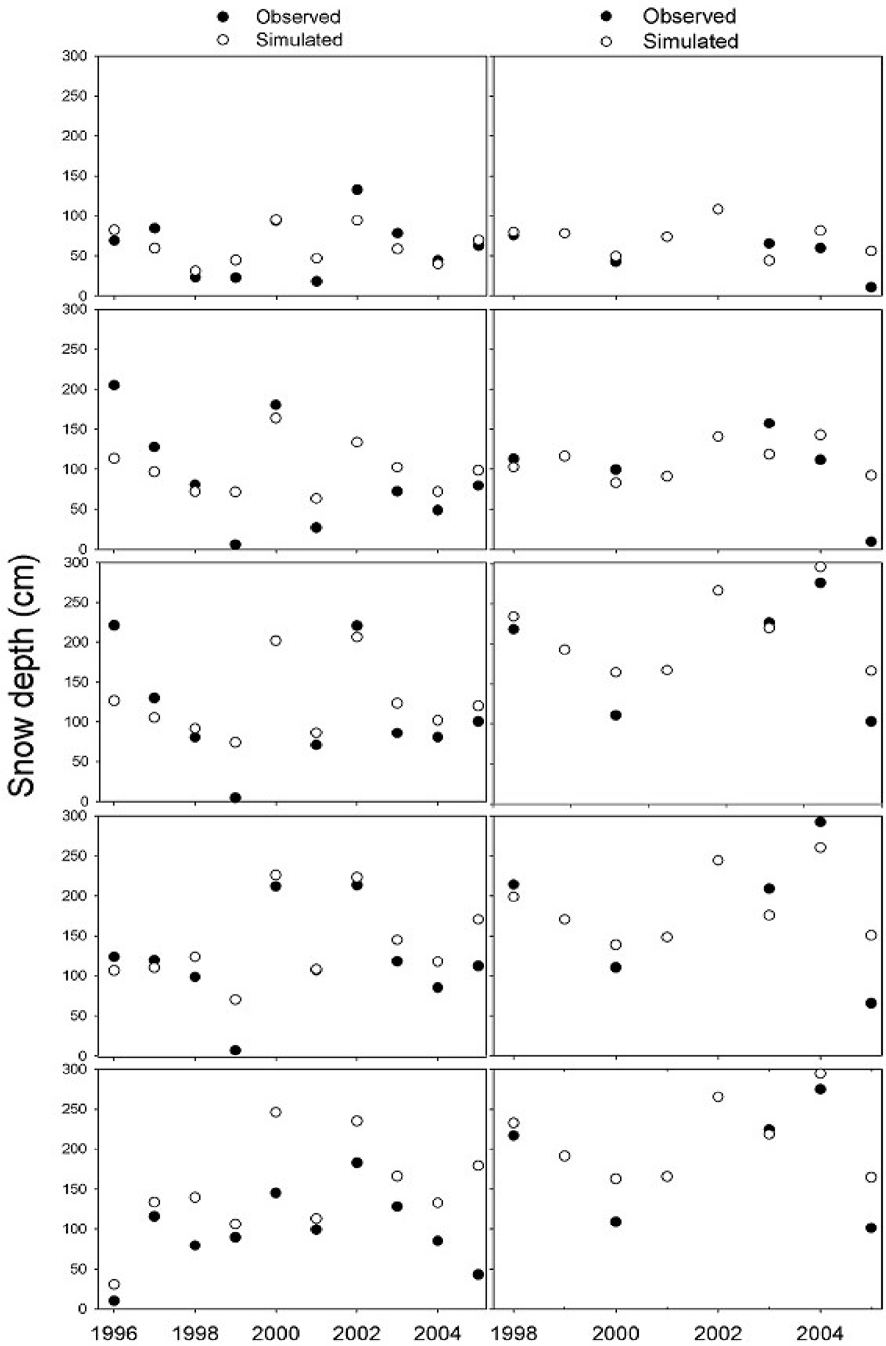


Figure 5: Comparison of observed and simulated snow depths, based on automatic weather stations at Izas and La Bonaigua.

	D of Wilmott	R of pearson
Izas-Formigal		
December	0.86	0.84
January	0.78	0.80
February	0.85	0.83
March	0.91	0.90
April	0.72	0.77
Bonaigua-Baqueira		
December	0.42	0.30
January	0.50	0.47
February	0.83	0.84
March	0.86	0.91
April	0.89	0.96

Table 4: Error estimates for the simulated monthly snow depth for the Izas and La Bonaigua weather stations.

3.2.4.2 Temporal evolution of climate and snow indices

Figures 6.1–6.3 show the long-term average values and the temporal trends for the 14 climate and snow parameters for each ski resort for the period 1960–2006.

Figure 6.1A shows the long-term average values and trends in the frequency of days when the snow depth (not including snowmaking) exceeded 30 cm at the base of each ski station. The average number of days exceeding this threshold per season ranged from 46 to 138 days; for 7 out of the 11 stations analyzed it exceeded 100 for the lowest elevation, indicating they were viable under the ‘100 days’ rule. All stations showed a decreasing trend in the number of days when the snow depth was thicker than 30 cm, but this was only statistically significant for 5 ski stations, which coincided with those having the lowest number of days above this threshold. Figure 6.1B shows the trend and frequency based on a threshold of 100 cm snow depth. The number of days on which this threshold was reached was much lower (from 1 to 77 days, depending on the station), and the negative trends were much steeper, with decreases ranging from 40 to 100% depending on the station. The westernmost ski stations and the stations having the most continental climates showed the steepest trends.

Figure 6.1C and 6.1D shows comparable results to those presented in 6.1A and 6.1B, but based on the middle elevation sites for the various ski stations. The majority of stations had almost 4 months when the snow depth was > 30 cm, and all but one had > 100 cm snow depth for at least two months. For all stations the number of days having snow depths of 30 cm and 100 cm at the middle elevation decreased over the study period. This decrease was statistically significant at two stations with respect to the 30 cm threshold, and four stations with respect to the 100 cm threshold; all these stations being in the westernmost part of the study area.

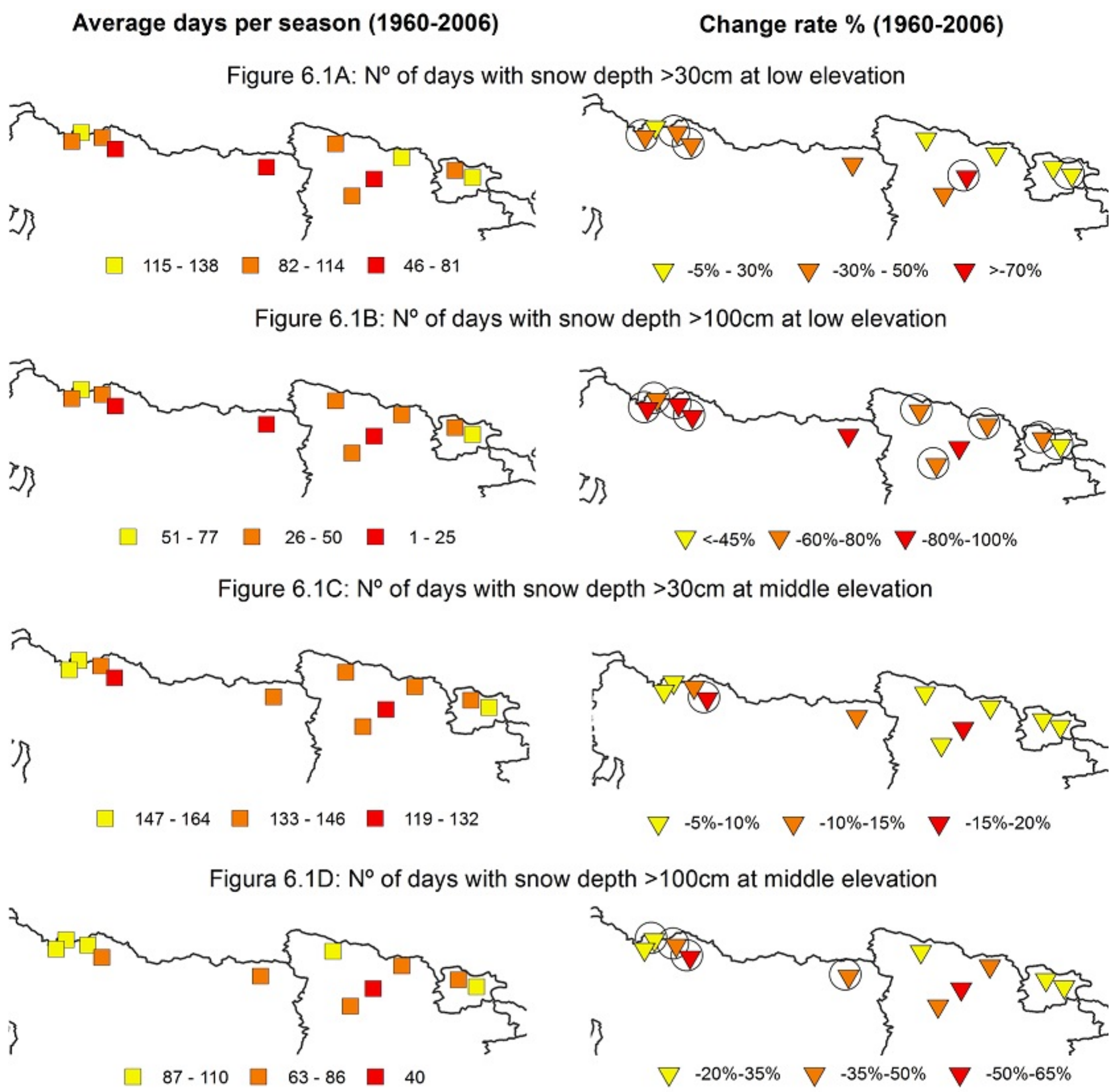


Figure 6.1: Long-term average values and trends in the frequency of days when the snow depth exceeded the 30 cm and 100 cm snow depth thresholds. The maps on the left show the long-term average value for each variable for the period 1960–2006, whereas the maps on the right show the magnitude of change. Up/down triangles indicate positive/negative trends (increasing or decreasing). The triangle color indicates the degree of change: yellow, slight; orange, moderate; red intense. Statistically significant changes are circled.

Figure 6.2A and 6.2B show the number and trend in the length (number of days) of the ski season at low elevation. Without the use of snowmaking, few stations could open at the base of the station in early December and remain open beyond early April. A delay in the start of the season from 5 to 55 days occurred during the study period; the largest change occurred for the westernmost stations. Trends show that closure dates have occurred earlier in the season (range: 24–42 days). The changes were statistically significant for 6 stations, some of which are located in the eastern Pyrenees.

Figure 6.2C and 6.2D show the number and trend in the length (days) of the ski season at middle elevations. The majority of the stations were able to open in early December and remain open until the middle or end of April. The trends show the beginning of the season has been delayed by 5–30 days, and the delay was statistically significant for two stations. There was also a tendency for earlier closure dates (in average, 21 days).

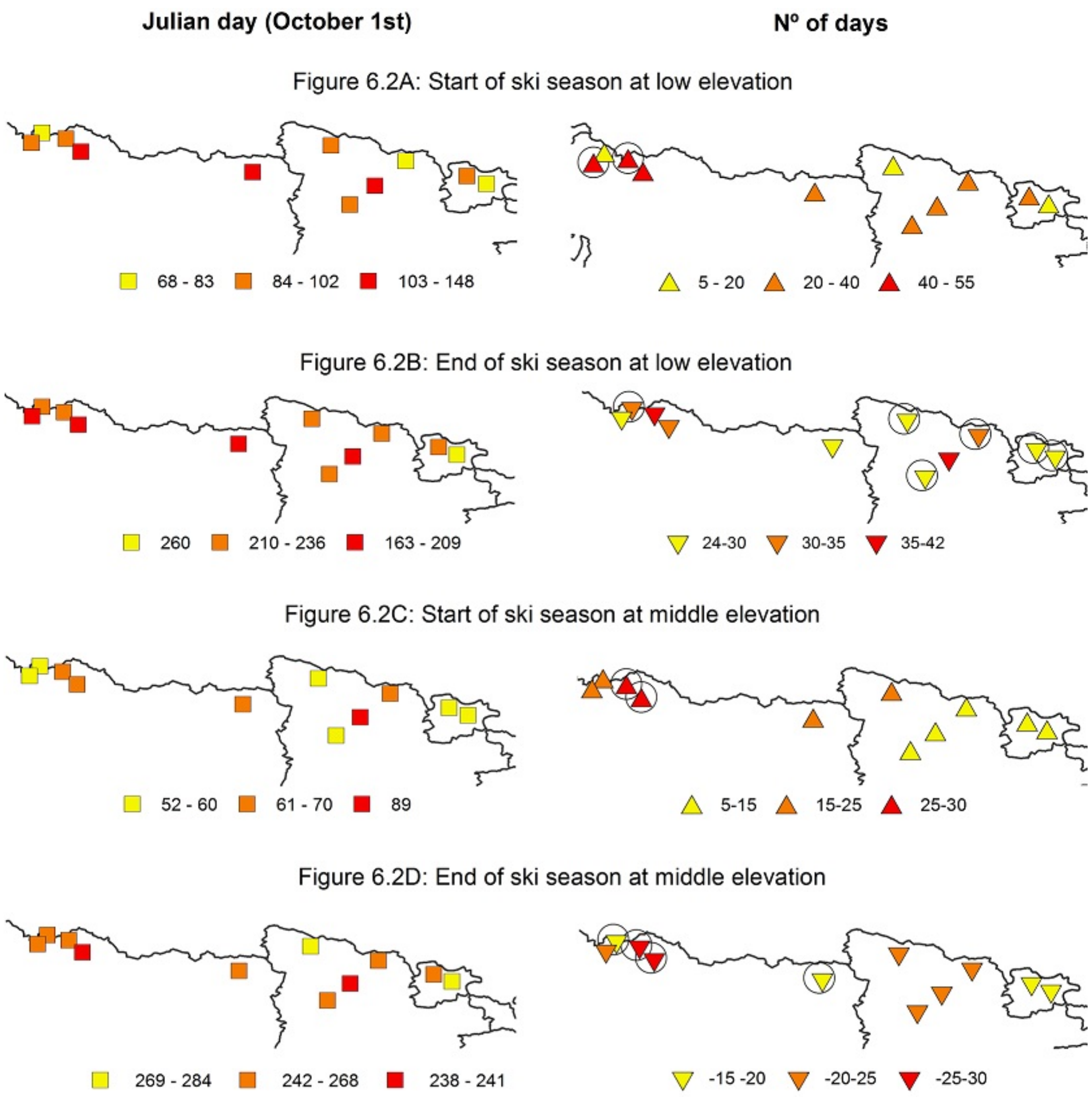


Figure 6.2**:** Long-term average values and trend of days in the length of the ski season at low and middle elevations. The maps on the left shows the Julian day for the beginning and end for each variable for the period 1960–2006, whereas the maps on the right show the number of days of change. Up/down triangles indicate positive/negative trends (increasing or decreasing). The triangle color indicates the degree of change: yellow, slight; orange, moderate; red intense. Statistically significant changes are circled.

Figure 6.3A shows the number of rainy days (rainfall > 10 mm) at low elevation sites at each of the stations. This parameter ranged for 2 to 7 days, and there were no clear differences among stations. Interestingly, for a group of stations the number of days increased during the study period, whereas for others it decreased with no apparent geographic pattern. Figure 6.3B shows the number of days on which the snowfall was > 10 cm during operating hours. The stations most exposed to fronts from the north and northwest had the greatest number of days with snowfall > 10 cm. The trend throughout the study showed that 8 stations (the westernmost) had an increase in the number of days (1–85% increase), whereas at 3 stations such snowfall events declined by 9–27%.

Figure 6.3C and 6.3D show the number of hours on which conditions for reliable snowmaking occurred at the low and middle elevations at the ski stations. At the low elevation the number of hours ranged from 1093 to 2230 per season, with only two stations exceeding 2000 h. At the middle elevation the number of hours ranged from 1878 to 2982. During the study period a trend of decrease in the number of hours occurred at both the low and middle elevations, but was greater (range –12% to –20%) for the former than at the latter (–8% to –15%). However, the negative trend for the middle elevation was statistically significant for the majority of ski stations.

Figure 6.3E shows the number of days per season when a wind-chill <–20°C was recorded at middle elevations. The number ranged from 3 to 18 days, with variability mostly related to the eastward increase in the mean elevation of the ski stations. There was a clear trend towards less intense cold days, but the change was not statistically significant for any station. Figure 6.3F shows that over the study period there was a trend to fewer days when wind speed exceeded the long-term 80th percentile, with the exception of one station. This decrease was statistically significant for 5 stations, but no geographic pattern was evident.

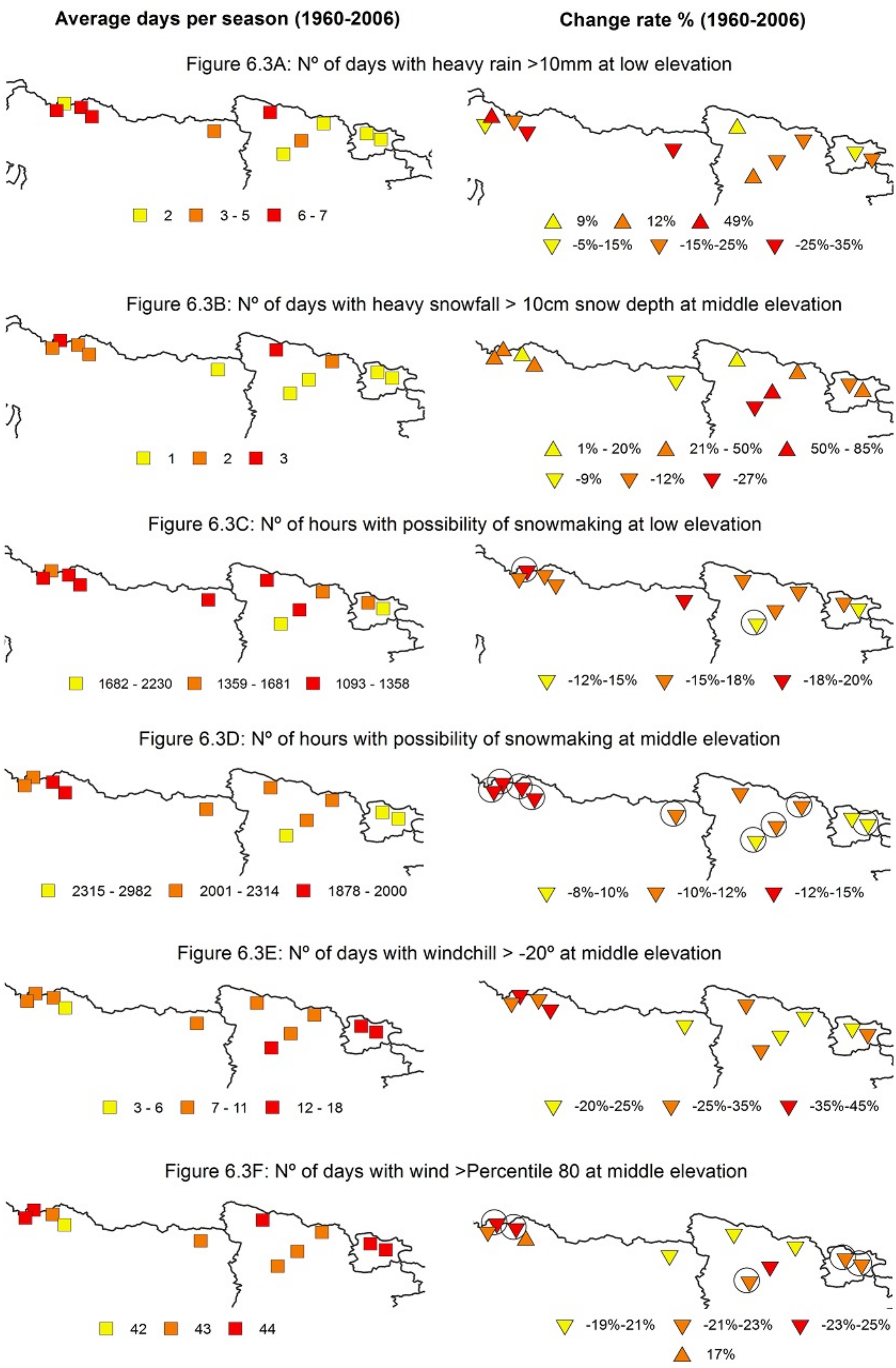


Figure 6.3: Long-term average values and trends for various skiability parameters at the 11 ski stations in the study. The maps on the left show the long-term average value for each variable for the period 1960–2006, whereas the maps on the right show the magnitude of change. The triangle color indicates the degree of change: yellow, slight; orange, moderate; red intense. Statistically significant changes are circled.

The PCA based on the data summarized in Figures 6.1–6.3 revealed two groups of ski stations having similar trends in the 14 analyzed parameters (Table 5). We found that 2 components (PC1 and PC2) accounted for > 90% of the variance. Table 5 shows the factorial loadings for PC1 and PC2 for each of the ski stations. PC1 comprised 6 stations: Grandvalira (0.92), Tavascán (0.89), Vallnord (0.85), Boí Taüll (0.82), Baqueira Beret (0.82), and Astún (0.81), whereas PC2 comprised 4 stations: Cerler (0.90), Espot Esquí (0.84), Panticosa (0.83), and Formigal (0.73). The Candanchú station showed almost equal correlation with PC1 and PC2.

SKI STATION	PC1	PC2
ASTÚN	**0.81**	0.52
BAQUEIRA BERET	**0.82**	0.40
BOÍ TAÜL	**0.82**	0.42
CANDANCHÚ	**0.68**	**0.69**
CERLER	0.35	**0.90**
FORMIGAL	0.62	**0.73**
GRANDVALIRA	**0.92**	0.30
PANTICOSA	0.35	**0.83**
ESPOT ESQUÍ	0.31	**0.84**
TAVASCÁN	**0.89**	0.38
VALLNORD	**0.85**	0.31

Table 5: Factorial loadings obtained in the principal components analysis. The use of bold is only to highlight the number over the plot of the cell. The dotted cells indicate the stations that are most correlated with PC1, cells filled with lines indicate the stations that correlate most with PC2. Those stations that show dotting and line filling correlate similarly with both PC1 and PC2.

Based on Figures 6.1–6.3, the stations having major factorial loadings in PC1 were those that over the study period had a lesser decrease in snow depth, only a small reduction in the length of the ski season, and most hours where there was the possibility for snowmaking. Those stations clustered in PC2 showed a clearer trend towards suboptimal skiing conditions (fewer days with appropriate snow depth, and less potential for snow making).

Figure 7 shows the main differences in the trends for the 14 parameters for the stations most highly correlated with PC1 (Grandvalira) and PC2 (Cerler).

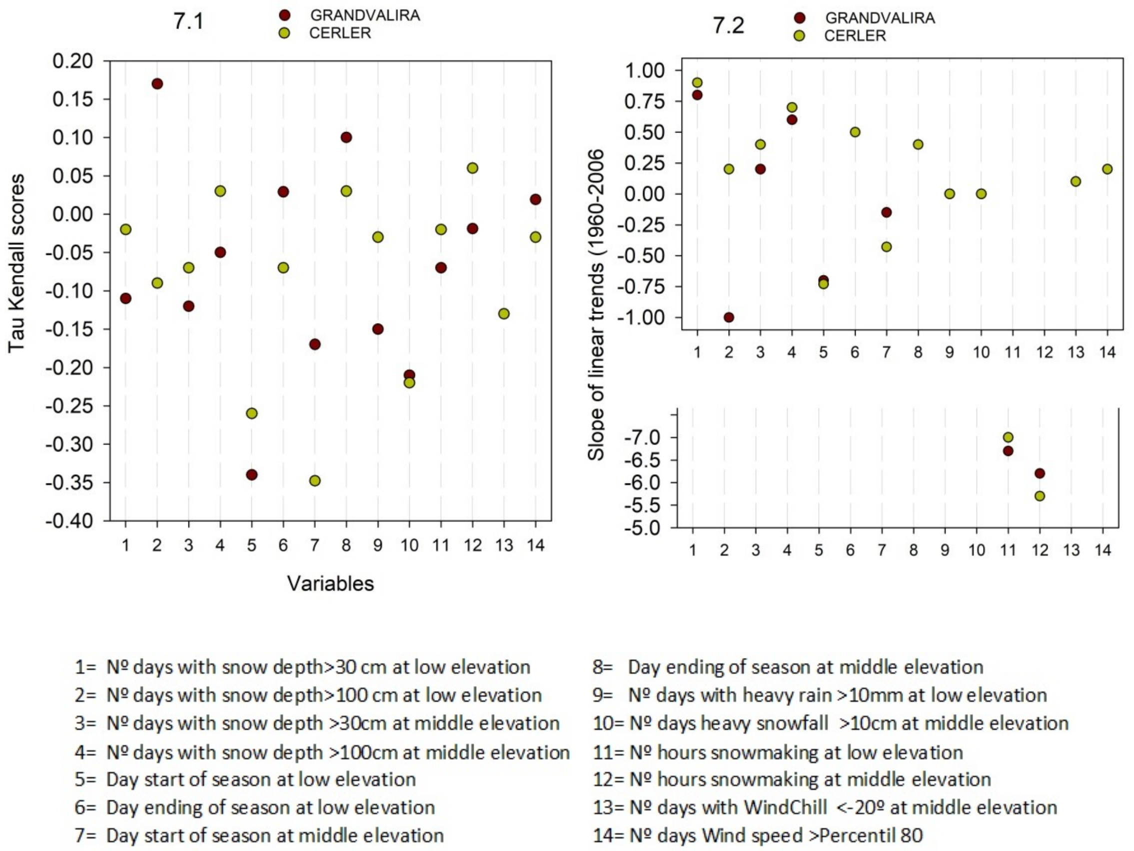


Figure 7: Tau Kendall coefficients and linear trends for the period 1960–2006 for the 14 analyzed snow and climate parameters for the stations Grandvalira and Cerler. Figure 7.1 shows the Tau Kendall coefficients: the X axis shows the Tau Kendall scores, and the numbers on the Y axis correspond to the 14 variables noted in the legend. Variables showing statistical significance ($p < 0.05$; values < –0.20 and > 0.20) are enclosed by a circle. Figure 7.2 shows the slope of the linear trends for the Grandvalira (PC1) and Cerler (PC2) ski stations. The slope for variables 11 and 12 are plotted separately because of the large difference in the magnitude of the X axis values relative to the other variables.

For Grandvalira station there was a significant decrease in the number of days having a snow depth > 100 cm at low elevation (tau = –0.37; –1 slope), length of the season at low and middle elevations (tau = –0.23 and –0.30; slope: –0.5 and –0.4, respectively), and the number of days having wind speed greater than the long-term 80th percentile (tau = –0.22; slope = –0.2). For Cerler station there was a significant decline in the number of days having a snow depth > 100 cm at the middle elevation (tau = –0.23; slope = –0.7), end date for the ski season at middle elevation (tau = –0.23; slope = –0.4), and the number of hours where there was the potential for snowmaking at the middle elevation (tau = –0.26; slope = –6.3).

The main difference evident between stations representatives of PC1 and PC2 was the change in the number of days with snow depth > 100 cm at low elevation. For Grandvalira station the tau value was –0.37 (statistically significant, $p < 0.05$), whilst for Cerler station this variable showed no statistically significant change. For Grandvalira station there was also a significant delay in the start of the skiing season; in the case of Cerler station this delay was not statistically significant. Moreover, at the latter station there was a statistically significant decrease in the number of potential hours for snowmaking at the middle elevation; this was not observed for Grandvalira station. Some mismatches between the trends based on the Kendall and linear regression methods were observed, including for variables 2, 6, and 9.

Figure 8 shows the elevation and the continentality (distance to the Cantabrian or Mediterranean seas) of the ski stations, and the PC to which each was most closely related. The ski stations located at higher elevations or closer to the sea masses were highly correlated to PC1, while stations at lower elevations or further from the sea masses were correlated with PC2. The Baqueira Beret station was an exception, probably because it is located in the only valley of the Spanish Pyrenees that faces fully north.

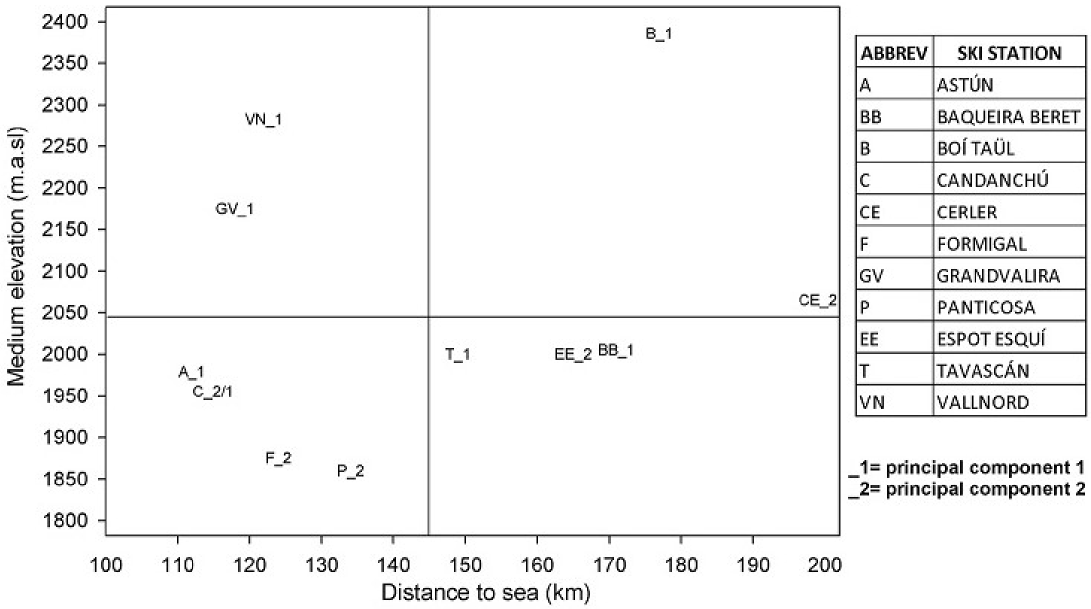


Figure 8: Elevation and continentality of the ski stations. The terms _1 and _2 indicate that the station was more highly correlated with PC1 or PC2, respectively. The horizontal and vertical lines represent the average values in elevation and distance to the sea for all ski stations.

3.2.4.3 Temporal association in the occurrence of snow and climate conditions

To assess whether the frequency of a given snow or climate variable in a particular year was positively or negatively associated with other variables, we used a correlation matrix for each ski resort to analyze the correlations among the 14 snow and climate variables considered in the study. To simplify the presentation of results we conducted a PCA to group stations having similar correlation matrices. This analysis (Table 6) distinguished two PCs, for which the station grouping was the same as that found for the PCA of the temporal trends of the variables. Thus, PC1 grouped the stations located at high elevation or close to the sea masses, including Vallnord (0.94), Baqueira Beret (0.90), Tavascán (0.87), Grandvalira (0.83), Boí Taül (0.79), Astún (0.77), and Candanchú (0.68), while PC2 grouped stations at lower elevations or which are more continental, including Espot Esquí (0.90), Cerler (0.89) and Panticosa (0.81). The Formigal station showed a similar correlation with each of the two principal components. As an example, Figure 9 shows the correlation matrix for the Vallnord (highly correlated with PC1) and Cerler (highly correlated with PC2) stations.

SKI STATION	**PC1**	**PC2**
ASTÚN	**0.77**	0.48
BAQUEIRA BERET	**0.90**	0.24
BOÍ TAÜL	**0.79**	0.41
CANDANCHÚ	**0.68**	0.60
CERLER	0.33	**0.89**
FORMIGAL	**0.68**	**0.66**
GRANDVALIRA	**0.83**	0.44
PANTICOSA	0.38	**0.81**
ESPOT ESQUÍ	0.21	**0.90**
TAVASCÁN	**0.87**	0.35
VALLNORD	**0.94**	0.35

Table 6: Factorial loadings of the PCA based on correlation matrix analysis. The use of bold is only to highlight the number over the plot of the cell. The dotted cells indicate the stations that are most correlated with PC1, cells filled with lines indicate the stations that correlate most with PC2. Those stations that show dotting and line filling correlate similarly with both PC1 and PC2.

VALLNORD

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.0	0.5	0.5	0.5	-0.9	0.1	-0.5	0.0	0.1	0.1	0.2	0.2	0.2	0.2
2		1.0	0.1	0.6	-0.5	0.2	-0.3	0.0	0.1	0.5	0.2	0.1	0.4	0.6
3			1.0	0.3	-0.4	0.0	-0.7	0.0	0.0	0.0	0.1	0.1	0.0	0.0
4				1.0	-0.6	0.0	-0.6	0.0	0.1	0.3	-0.1	-0.1	0.2	0.3
5					1.0	0.1	0.7	0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
6						1.0	0.2	1.0	0.0	0.2	0.3	0.3	0.3	0.2
7							1.0	0.2	-0.2	0.0	0.0	0.1	0.0	0.1
8								1.0	-0.1	0.1	0.2	0.1	0.2	0.0
9									1.0	0.2	-0.2	-0.2	0.0	0.0
10										1.0	0.1	0.1	0.3	0.4
11											1.0	0.9	0.6	0.3
12												1.0	0.5	0.3
13													1.0	0.5
14														1.0

CERLER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.0	0.3	0.4	0.6	0.2	0.7	-0.3	0.1	0.0	-0.1	0.3	0.3	0.4	0.6
2		1.0	0.1	0.2	-0.1	0.3	-0.1	0.2	0.1	-0.1	0.1	0.3	0.1	0.2
3			1.0	0.6	0.3	0.3	-0.7	0.2	0.3	-0.4	0.3	0.2	0.3	0.3
4				1.0	0.1	0.4	-0.6	0.2	0.3	-0.2	0.1	0.0	0.2	0.4
5					1.0	0.7	0.0	0.4	-0.1	-0.1	0.3	0.3	0.2	0.3
6						1.0	-0.1	0.5	-0.1	-0.2	0.4	0.3	0.4	0.5
7							1.0	0.1	-0.3	0.4	0.0	0.1	-0.1	0.0
8								1.0	0.0	-0.2	0.3	0.2	0.3	0.2
9									1.0	-0.1	-0.3	-0.3	-0.2	0.1
10										1.0	0.0	0.2	-0.2	0.1
11											1.0	0.9	0.7	0.4
12												1.0	0.5	0.5
13													1.0	0.5
14														1.0

Positive correlation
Negative correlation

1= Nº days with snow depth>30 cm at low elevation
2= Nº days with snow depth>100 cm at low elevation
3= Nº days with snow depth >30cm at middle elevation
4= Nº days with snow depth >100cm at middle elevation
5= Day start of season at low elevation
6= Day ending of season at low elevation
7= Day start of season at middle elevation
8= Day ending of season at middle elevation
9= Nº days with heavy rain >10mm at low elevation
10= Nº days heavy snowfall >10cm at middle elevation
11= Nº hours snowmaking at low elevation
12= Nº hours snowmaking at middle elevation
13= Nº days with WindChill <-20º at middle elevation
14= Nº days Wind speed >Percentil 80

Figure 9: Correlation matrices for the Vallnord and Cerler stations, based on climate variables and snow-related data for the period 1960–2006. The numbers on the axes represent each of the 14 analyzed variables listed in the legend. The number in each cell is the correlation value. The colors indicate significant correlations: orange for correlations > 0.20 and blue for correlations < –0.20. Cells having thick borders represent positive or negative correlations exceeding 0.60 (+/–).

For Vallnord station there was a positive correlation between the variables related to snow depth at both low and middle elevations (1-2, 1-3, and 1-4). For the years having greater snow depths there was a strong correlation with earlier opening and later closing dates (1-5, 1-7). In addition, the years having a thicker snowpack were associated with better conditions for snowmaking, and more frequent cold and windy days. Thus, for years in which the snowpack was thinner there was less likelihood of station closure because of adverse weather conditions.

The Cerler station (closely related to PC2) showed interesting differences compared with the PC1 stations. For example, the abundance of snow was not necessarily related to earlier opening of the ski resort (2-5), and there were years when the potential for snowmaking was lower. For Cerler station the years having more snow at the lower elevation were more clearly correlated with more frequent windy days, compared with Vallnord station. Moreover, greater snow depth at middle elevation could be correlated in some years with the occurrence of rainy days at the lower elevation at the ski resort. At this station a higher frequency of very cold days (low wind-chill temperatures) was slightly correlated with lower frequencies of snowfall and rainy days (–0.2). Years having most rainy days had fewer potential hours for snowmaking, and fewer days when the wind-chill temperature was < –20°C.

3.2.5 Discussion and conclusions

In this study we assessed temporal changes in snow and climatic variables related to skiability at 11 ski stations in the Central Pyrenees. We also analyzed the temporal association in the annual occurrence of these variables. Because of the lack of observational data for the region we used simulations from a high-resolution hindcast climate simulation to undertake analysis for the period 1960–2006. Prior to the analysis it was necessary to check the reliability of the simulated climate data, and the snowpack simulated using the Snobal snow energy and mass balance model. In general, the results confirmed that the majority of the simulated climatic variables closely matched the observed temperature and precipitation data (fit values of 0.72 and 0.96, respectively). Greater uncertainty was associated with relative humidity, and a bias correction was necessary for the simulated wind speed. The simulated snow depth showed a high level of agreement with observed data, which further confirmed the robustness of climate simulation and the ability of the Snobal model, implemented in the CRHM platform, for simulating the snowpack in the Pyrenees (López-Moreno et al., 2013; 2014).

The number of days having a snowpack thicker than 30 cm and 100 cm declined markedly at all ski stations during the study period, at both the low (5–70% and 42–100%, respectively) and middle (4–20% and 20–65%, respectively) elevations. For the same period a reduction in snow depth in the Mediterranean mountains has been reported (López-Moreno et al., 2011), particularly in the Pyrenees (López-Moreno, 2005; Pons et al., 2012).

Under natural snow conditions the start of the ski season has clearly been increasingly delayed at low (5–55 days) and middle (5–30 days) elevations. This delay may have markedly reduced annual incomes, and during the current Spanish festive period of 6–8 December there is substantial dependence on snowmaking. Based on natural snow, the ski season would open between 24 December and 11 January at 72% of the ski stations. This is relevant because the success or failure of a ski season is determined by the ability of the stations to be operational, especially during the Christmas holidays (Dawson and Scott, 2013; Steiger and Abegg, 2013).

The frequencies of rainy days and days having heavy snowfall were more variable. The occurrence of rainy days increased by 9–49% at 3 stations, but decreased by 5–35% at 8 stations. The difference in the sign of the trends is related to the coincidence of temperature and precipitation under mild weather conditions (Vicente-Serrano and Lopez-Moreno, 2007), and a decrease in winter precipitation (Dünkeloh and Jacobeit, 2003). In addition, those stations showing a greater reduction in days of operation also showed a reduction in the number of days on which rainfall occurred during operating hours.

At the westernmost ski stations the number of days of heavy snowfall increased by 1–85%, but at three stations heavy snowfall events declined by 9–27%. López-Moreno et al. (2011) indicated that a warmer climate may lead to intensification of precipitation extremes, with a generalized trend of increase in intense daily events that may result in snowfall at higher elevations. A robust relationship between elevation and the sign of change in heavy snowfall has also been observed in the Swiss Alps, and this trend has been increasing since

1960 at higher elevations (Beniston, Keller, Koffi and Goyette, 2003; Laternser and Scheebeli 2003).

To calculate the potential for snowmaking we used a –2°C wet-bulb temperature threshold; this threshold has been used in previous studies (Olefs, Fischer and Lang, 2010; Steiger and Mayer, 2008), although more recently a threshold of –1.7°C has been used (Hendrikx and Hreinsson, 2012). The results showed that the number of hours when there was the potential for snowmaking declined by 8% and 20% at middle and low elevations, respectively. Although the production of artificial snow is not able to counter all the impacts of climate change on the snowpack, this is a key factor in evaluating the viability of ski stations (Pons et al., 2015); snowmaking is now the most important mitigation strategy. Its use has increased in recent years, and it is currently applied over large areas at many ski resorts (Steiger and Mayer, 2008).

Wind speed is another important variable determining skiable conditions; it is the main reason for the closure of ski lifts, and on some days prevents the resort from opening. Our results showed a general decrease (19–25%) in the number of days per season that exceeded the long-term 80th percentile for wind speed at all ski stations except Panticosa. Many studies worldwide have reported a decline in the near-surface wind speed (so called global stilling; summarized by Roderick, Rotstayn, Farquhar, and Hobbins, 2007, and McVicar et al., 2012). For the period 1960–2006, McVicar et al. (2010) noted that this stilling process is more rapid at higher elevations. For the Iberian Peninsula, Azorín-Molina et al. (2014) found that there has been a trend of decreasing wind speed in winter and spring (coinciding with the ski season).

Wind-chill, which is influenced by air temperature, has increased markedly in this region in recent decades (El Kenawy, López-Moreno, and Vicente-Serrano, 2012; López-Moreno et al., 2011b;), and is directly correlated with wind speed. Thus, the observed decline in the number of days with wind-chill < –20°C (range among stations: 20–45%) is not surprising, especially at the base level of the ski stations. Trends of decrease in both wind speed and wind chill are generally associated with improved economic profitability of ski stations.

Many of the detected trends must be interpreted in the context of decadal variability in climate, which makes the results very dependent on the selected study period, and particularly the influence of the main atmospheric patterns (e.g. the North Atlantic Oscillation; NAO) on the climate of a specific area (Jerez and Trigo, 2013; Muñoz-Diaz and Rodrigo, 2003; Vicente-Serrano, 2011). For instance, several recent studies in the Pyrenees have reported that there was no decrease in snow in the French Pyrenees during the second half of the 20th century, while the influence of the NAO on precipitation was almost opposite to that observed on the Spanish side of the Pyrenees (Maris, Giraud, Durand, Navarre and Mérindol, 2009). Furthermore, the trends for snow on the Spanish side have been neutral in recent years, as a consequence of the increased occurrence of negative NAO winters during the last decade (Buisan, Saz, and López-Moreno, 2015; El Kenawy et al., 2012). However, most of the climate models project a trend of increase, superimposed on inherent fluctuations (Beniston, 2005; López-Moreno et al., 2008; López-Moreno et al., 2009). Furthermore, climate projections for the Pyrenees suggest marked warming

(Ribalaigua, et al., 2013) that will affect the snowpack, especially at low and middle elevations (1550–2000 m a.s.l.), where many ski slopes are located (López-Martín, 2011; López-Moreno et al., 2009; Nogués-Bravo, Lasanta, López-Moreno and Araujo, 2008; Pons et al., 2012, 2015).

The PCAs identified two groups of ski stations having similarities in trends and annual association in the frequency of the 14 parameters considered in the study. Those stations located closer to the main divide of the Pyrenees, at higher elevations, or having less continentality (i.e. closer to the Atlantic Ocean) showed a lesser decrease in the snow depth, and the timing (start and end) of the ski season. For example, at Vallnord station there was little variation in those variables for the period 1960–2006. Pons et al. (2015) also reported that proximity to the Atlantic Ocean will have a marked influence on the vulnerability of various ski resorts to projected climate change in the Pyrenees over coming decades. The stations located at lower elevations and more inland showed steeper trends towards reduced skiability, including reduced snow depth, duration of cover, snowmaking potential, and very cold days (wind-chill < –20°C), although the latter can increase the economic return to affected ski resorts on some days during the ski season.

Our analysis showed that there were associations among variables. The positive correlation of snow rich years to the frequency of windy days (Pearson's r > 0.6) and good conditions for snowmaking was particularly important. This indicates that in general the windiest years are also the coldest and most snow rich years. The seasons having major cold spells result in lower frequencies of heavy snowfall and intense rainfall (–0.2). This is consistent with the findings of Buisan et al. (2015), who reported that winters dominated by northerly flows have lower humidity and temperatures in the southern part of the range, because flows from this direction are blocked by the mountain divide.

Although some studies have investigated changes in the snowpack in the Pyrenees, studies of other ski-related variables have not been undertaken. This is partly explained by the absence of reliable long-term data series for these variables. Very few studies have considered skiability and ski tourism in relation to temporal associations with climate variables. However, this is a key issue in developing a broader and more accurate picture of the impacts of climate change on skiing. How these climate variables affect future demand and tourism at ski stations is an important area of study that has not yet been addressed for the Central Pyrenees. Future studies should update the simulated data to the present, as such data are not available yet for the Pyrenees at high spatial resolution. These types of studies should be integrated with data on the behavioral response of skiers to specific climate and snow conditions. Moreover, it is necessary to integrate these studies with current techniques for managing snow on ski slopes, which will enable refinement of adaptation measurements in mountain regions, and by ski companies facing climate variability and change.

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3.3 RELATIONSHIP OF ATTENDANCE AT THREE SKI STATIONS IN THE CENTRAL PYRENEES WITH SNOW AVAILABILITY, HOLIDAY SCHEDULES, AND WEATHER CONDITIONS.

Abstract

We analyzed data on daily attendance of skiers and weather conditions at three ski areas in Central Pyrenees of Spain for the period 2003-2013. We characterized temporal variability of skiers attendance, and the relationship with snow availability and weather conditions.

The findings are that all ski station had large inter-annual variability in attendance, they were open an average of 130 days per year, with the start and end dates depended on holiday schedules. In addition, there were more than twice as many skiers on weekend as weekdays. About 75% of annual attendance occurred on 50% of the days in which the stations were open. Low snow availability is correlated with ski station closure, and windy conditions had the strongest influence in the attendance. The percentage of open ski runs also correlated with attendance; there were three-times more skiers when 75% of the ski runs were open relative to days when 25% were open.

KEYWORDS: Ski stations, Attendance, Concentration of skiers, Weather conditions, Spanish Pyrenees.

3.3.1 Introduction

Mountain tourism accounts for 20% of global tourism revenues, and winter tourism is a major activity in many mountain regions (Pickering, Castely, and Burtt, 2010). In particular, skiing is a major winter activity in about 70 countries, and there are about 2000 ski stations world-wide. The Alps are a major center for skiing, and have about 35% of all ski stations (Vanat, 2015). The most popular destinations for skiing are Austria, Switzerland, Italy, France, and Germany. There are about 350 million skiers worldwide, and the United States has more skiers than any other country. However, there has been a general trend of stagnation in attendance in most major markets, particularly during the 2013/14 season. Indeed, this period was a time of transition in the 6 largest ski markets (Vanat, 2015).

The ski market in Spain consists of 29 alpine ski stations, 990 ski trails, and 1012 km of trails. Most of these stations are in the Pyrenees and Sierra Nevada. The total number of skiers in Spain during the last decade ranged between 5 and 7 million per year. Similar to global trends, the ski areas in the Iberian Peninsula have also experienced decreases in attendance during the last five years. In addition, the economic crisis in Spain also affected its ski stations. Skiing in Andorra has also declined since 2006/07 (Vanat, 2015).

In northern Spain, the Pyrenees provide favorable conditions for skiing, and the popularity of skiing there has increased rapidly during the past 25 years. In particular, the Aragon region, the focus of this study, has had 1.2 to 1.8 million skiers per year during the last decade.

However, due to its latitude and geography, the Aragon region of the Pyrenees has experienced great seasonal variability in snow conditions, and therefore in attendance at ski station. This variability in attendance is mainly influenced by snow depth and weather conditions, but also due to socio-economic factors such as school holidays, which are almost always on the same dates. In fact, several researchers reported that climate and weather were the most important factors affecting the travel plans of tourists, and they also strongly influence the success of tourism businesses (Bank and Wiesner, 2011; Becken, 2010;Gomez-Marín, 2005; Nicholls, 2005; Rutty et al. 2015). Previous studies have used different meteorological factors or thresholds to assess the effect of weather on attendance of skiers at ski stations. For example, ski stations need a minimum snow pack of 30 cm to operate properly (Witmer, 1986). Other meteorological thresholds also affect attendance. For example, more than two consecutive days above 10°C with rain negatively affects attendance (Scott, McBoyle, Mills, and Minogue, 2006), high maximum wind speeds increase closure of ski lifts (Gilaberte-Búrdalo et al. 2017), and temperature and wet-bulb temperature affect snowmaking capability (Gilaberte-Búrdalo et al. 2017; Steiger, 2011).

Numerous studies have examined the impact of climate change on snow conditions. However, few studies have examined the effect of snow conditions on short-term attendance, and even fewer have considered the impact of other climatic variables, such as wind speed, wind-chill, and rain, on winter sports (Gilaberte-Búrdalo et al. 2017).

One of the most used methodologies to study the influence of climatic or meteorological factors on attendance at ski stations is the “climate analogues approach”. For example, Dawson, Scott, and McBoyle (2009) examined how a wide range of ski area performance indicators were affected by anomalously warm winters in the northeastern USA. They reported a 3.4% shorter ski season in 1998-1999 and an 11% reduction in 2001-2002. There were 11–12% fewer skiers in each of these time periods. Steiger (2011) examined the Austrian province of Tyrol, and found that extreme seasons, such as the 2006/2007 winter, had strong negative effects on ski stations at low elevations. He found 7% fewer operational ski days, an 11% reduction in ski lift transports, and a 7% decline in revenues. Overnight stays in the winter season of 2006/2007 decreased by 3% compared to the preceding three years. A subsequent study using the same methodology (Rutty et al., 2017) examined the ski industry during the record warm winter of 2011/2012 in the Ontario region. This warm winter represented a temperature anomaly of +3.7°C above average for the baseline period of 1981-2010. These researchers reported a 17% reduction in the duration of the ski season, a 3% reduction in use of operating ski lifts, and a 10% reduction in visits by skiers. Pickering (2011) examined the relationship of visitation patterns with snow cover at six ski areas in Australia during the 1997–2007 ski seasons. They found a 38% decline in visitation when there was low natural snow cover, even when there was snowmaking in a snow-scarce year (2006). The decreased visitation due to low snow cover is greatest in ski areas at the lowest elevations.

Other studies examined the statistical relationship of snow depth with ticket sales. Palm (2001) found that 700.000 fewer skiers visited ski areas in New Hampshire and Vermont during the years with the least snowfall, compared to years with the best snow depth. Other studies found that the annual number of skiers was significantly and positively related to the snow depth in the Swiss Alps (Abegg and Froesch,1994; Gonseth, 2013), Japan (Fukushima, Kureha, Ozaki, Fujimori, and Harasawa, 2002), and the Austrian Alps (Pickering, Castely, and Burtt, 2010). Falk and Hagsten (2016) studied the effect of early snowfall on the influx of skiers to ski stations in Sweden. They found that average snow depth was significantly associated with lift ticket sales in the early winter months of November, December, and January; in contrast, snow depth had no significant effect during the mid-season months of February and March or during the late season.

Some studies used overnight stays as an indicator of the number of skiers. For example, Falk (2010) studied the Austrian Alps and found that overnight stays increased as snow depth increased. In a subsequent study, Falk (2013) showed that the relationship between snow depth and skier visits may be non-linear. In agreement, Töglhofer, Eigner, and Prettenthaler (2013) also performed a study in Austria and reported the relationship of overnight stays with snow conditions. A 1% decrease in the snow index led to a decrease of less than 1% in overnight stays.

A few studies used other meteorological variables, rather than snow pack, to analyze variability in the attendance at ski stations. Shih, Nicholls, and Holecek (2009) provided one of the most complete studies in this area. They used daily data on weather conditions and ski lift ticket sales at two Michigan ski stations for the period 1996-2002, and found a positive and significant relationship of snow depth with sales of ski lift tickets. In particular, a 2.5 cm increase of snow depth correlated with a 9% increase of ticket sales, high temperature had a negative relationship with ticket sales (with a 2% decline in sales for each temperature increase of 0.5°C), and high wind-chill had a positive correlation with ticket sales (with a 1% of increase in sales for each 1°C decrease in wind-chill). In agreement, Beaudin and Huan (2014) reported that high winter temperature had a significant impact on closures of ski stations in New England. Falk (2013) examined the effect of cloudiness and hours of daily sunshine on skiing in the Austrian Alps. Sunshine, measured as the fraction of days with clear skies, had a negative impact on tourism. Moreover, more cloud cover led to increased domestic tourists, but fewer foreign tourists. Recently, Demiroglu, Kucerová, and Ozcelebi (2015) performed a study in Slovakia and found that a 1% decline in snow depth reduced ski pass sales by 1.2%, and a 1% decline in visibility reduced sales by 0.12%, indicating a relationship of demand with weather conditions. Moreover, a 1°C increase of the mean temperature correlated with a 6% loss of ski pass sales.

No studies have yet provided detailed analysis of the daily and inter-annual variability of skiers and their relationships with snow and weather conditions in the Pyrenees of Spain. In this study, we used daily data of three ski stations in the Pyrenees to examine the relationship of the number of skiers with snow and weather conditions, and the reasons for closure of ski runs. The three ski stations have different elevational gradients, overall size, and climatic conditions. The three of them together account for approximately 55% of skiers in the Aragon region. The study has two main parts. In the first part, we characterize the ski season duration and patterns of attendance, segregated by weekends and weekdays, and identify the impact of major holidays at the different ski stations. These data are important because it will help us predict the vulnerability of ski stations to lack of snow or adverse weather conditions during specific days of the winter season (Steiger, 2013). In the second part, we describe the influence of different weather parameters and the percentage of open ski stations in the daily attendance of skiers.

3.3.2 Study area

Our study focused on 3 ski stations (Panticosa, Formigal, and Cerler) located in the Aragon region of the central Spanish Pyrenees. The Pyrenees are in the northeast of the Iberian Peninsula, bounded by the Mediterranean Sea to the east and the Atlantic Ocean to the west. The Pyrenees extend over 425 km from west to east, and constitute a natural border between Spain and France. The width (north–south) in the central part of the range is 150 km, and is less in the western and eastern regions. Elevations vary from 500 m.a.s.l in some valley bottoms, to 3404 m.a.sl. at the summit of Aneto peak, and most of the region is above 1500 m.a.s.l. (López-Moreno and García-Ruiz, 2004). The elevation range of the ski stations is 1500 to 2600 m.a.s.l

The climate of the Pyrenees is influenced by the nearby Atlantic Ocean and Mediterranean Sea, on its west to east axis. However, the abrupt relief causes great spatial variability in the distribution of precipitation and temperature. Close to the main divide and the Pyrenean summits, precipitation exceeds 1000 mm per year, and can reach more than 2000 mm per year in some areas (Cuadrat, Saz, Vicente-Serrano, and González-Hidalgo, 2007); however, there is a general pattern of decreasing precipitation from west to east and north to south (Buisán, López-Moreno, Sanz, and Korchendorfer, 2016). Precipitation usually falls as ice or snow from late autumn to early spring above 1500-1600 m.a.s.l. (López-Moreno and García-Ruíz, 2004). Temperature also declines with increasing elevation, and Del Barrio, Creus, and Puigdefabregas (1990), estimated a decline of 0.68°C for each 100 m of altitude. From November to April, the 0°C isotherm is at approximately 1600–1700 m.a.s.l. Below this limit, snowpack occurs only during the coldest months of winter (December to February). Below 1300 m.a.s.l., the snowpack is generally ephemeral, even though snowfall events are common during winter (Navarro-Serrano and López-Moreno, 2016). Wind is also an important climatic element in the Pyrenees, and it usually blows from the northwest, and to a lesser extent from the north, west, and east (López-Moreno and Vicente-Serrano, 2006). When weather fronts enter from the north and northwest, most moisture falls in the north, and near the main divide of the Pyrenees (normally following the French–Spanish border). As a consequence of the Foehn effect, dry and warm air masses arrive at the southern slopes of the Spanish Pyrenees. This results in marked differences between the Spanish and French mountain ranges in terms of snow accumulation, occurrence of sunny days, and wind-chill, all of which directly affect the conditions at ski stations and the number of skiers (Gilaberte et al. 2017).

The three ski stations analyzed in this study are Formigal, Panticosa, and Cerler. Since 2014-2015 season, the ski stations of Formigal and Panticosa merged into a single skiing domain; however, they are not physically linked by ski slopes, but by a road with a separation of 12 km, with Panticosa located further south. Formigal previously enlarged its size in the 2007-2008 season, and is now the largest of these stations, with 137 km of ski runs and a capacity of nearly 40.000 skiers/h. The elevation range at Formigal is 1500 to 2250 m.a.s.l.

Panticosa is the smallest of the three stations. It has 36 km of ski runs, and a capacity of about 14.000 skiers/h. Its elevation ranges from 1500 to 2200 m.a.s.l. Despite its proximity to Formigal, it has very different topographic and climatological characteristics, in that it is very sheltered from northern and northwestern weather fronts but is very vulnerable to wind because access is only possible via a cable car that does not operate when wind gusts exceed 60 km/h (Gilaberte et al. 2017).

Cerler is in the eastern part of the Aragon Pyrenees. Its highest point is 2630 m.a.s.l., although most of the station lies between 1900 and 2300 m.a.s.l. It has 77 km of ski trails and a capacity of about 26.000 skiers/h, (ATUDEM, 2017).

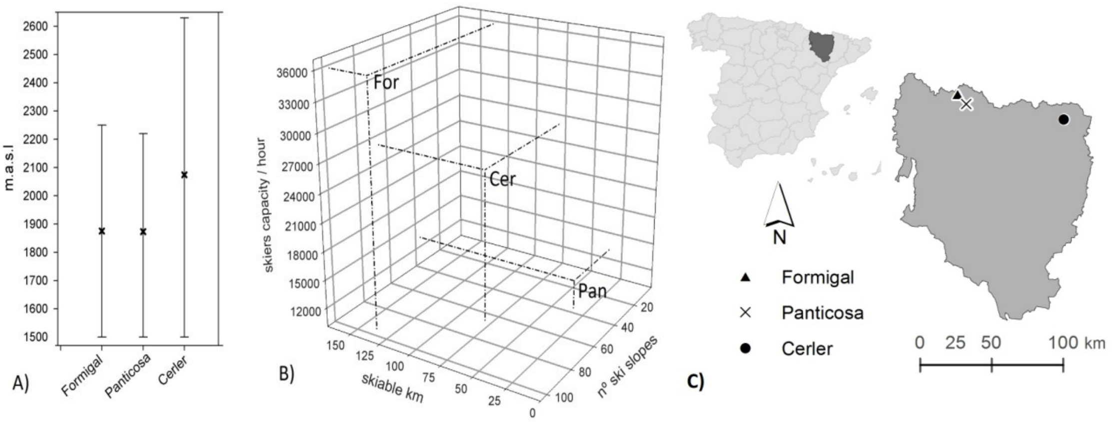


Figure 1: Basic characteristics of the three ski stations. A, elevation ranges; B, number of ski trails, skiable trails (km), and capacity (skiers/h); C, geographical locations.

3.3.3 Data and methodology

3.3.3.1 Data

This study used high-resolution daily data of different skiing-related parameters from the three ski stations during the seasons 2003-2004 to 2013-2014. All data were provided by a consortium representing skiing businesses in Aragon (ARAMON S.L.). Table 1 summarizes the data used for analysis (number of skiers, opening and closure dates, and motives for closure, weather conditions, and open trails).

3.3.3.2 Statistical analysis

The two first parts of the Results (3.3.4.1 and 3.3.4.2) provide a statistical descriptive analysis of the start, end, and duration of the ski season, the frequency and main reasons for closure, and temporal concentration and patterns of skiers. The second part of the Results (3.3.4.3) provides a bivariate analysis of the patterns of attendance. More specifically, we tested the associations between the number of skiers with different weather conditions and the percentage of open trails at each station using analysis of variance (ANOVA). This allowed determination of statistically significant differences in the means of different groups.

An F-test was used to determine the significance of differences. When mean values are equal, F has a value of 1; if they differ, F has a value greater than 1. The value of the F statistic is presented with its level of significance (p-value.) p-value below 0.05 led to rejection of the assumption of similar means (Rubio-Hurtado and Berlanga-Silvente, 2012).

Different *post hoc* (*a posteriori*) tests can be used to determine which means differ from others when the general hypothesis is rejected. We used the Bonferroni method to correct for multiple comparisons. This method controls the error rate by dividing the level of significance (α) by the number of comparisons (k). Thus, each comparison was evaluated using a significance level α C = α/k. (Dunn, 1961).

DATA	DESCRIPTION	TYPE	RESOLUTION	PERIOD	SOURCE
Number of skiers	Number of people who obtain lift tickets for all or any part of a day.	Quantitative	Daily	2003-2013	ARAMON S.L
Number of open days	Number of days the ski station is open during the ski season.	Quantitative	Daily	2003-2013	ARAMON S.L
Number of closed days	Number of days the ski station is totally closed.	Quantitative	Daily	2003-2013	ARAMON S.L
Motives for closure	The main reason for closure.	Qualitative	Daily	2011-2013	ARAMON S.L
Weather type	Description of the weather conditions each day, based on the observations of a meteorologist rather than a meteorological observatory.	Qualitative	Daily	2011-2013	ARAMON S.L
Open ski runs (km)	Number of open ski runs (km) in one day.	Quantitative	Daily	2011-2013	ARAMON S.L

Table 1: Data used for analysis of three ski stations in the Central Pyrenees.

3.3.4 Results

3.3.4.1 Variability of ski season duration from 2003-2013

3.3.4.1.1 Start, end, and length of ski season

Figure 2 shows the variability of the start, end, and duration of the ski seasons in 2003-2013, and Table 2 shows the absolute and relative frequency of the start, end, and duration of the season. In most years, the start at each station was in the first week of December (n = 19, 58%) or the last week of November (n = 8, 24%). In recent years, there was a trend of opening the first week of December rather than the last week of November. The Cerler station had more inter-annual stability in opening date than those at Panticosa and Formigal. Figure 2B shows the end of the ski season, and the red dots indicate the occurrence of Easter week. In 82% of years, the ski season ended in the first 3 weeks of April. Cerler and Formigal remained open until late April, but Panticosa only remained open until the third week of April during 2 years. In general, there were no clear changes over time in the day of closure, but the Easter holiday was typically the last date of high attendance.

Figure 2C shows the duration of the ski season. The dotted line represents the average (130 days) of all 3 stations over 11 years. The duration of the snow season had greater inter-annual variability than the opening and closure dates. The Cerler station had the longest ski seasons (range: 121-160 days), followed by Formigal (100-160 days) and Panticosa (100-140 days).

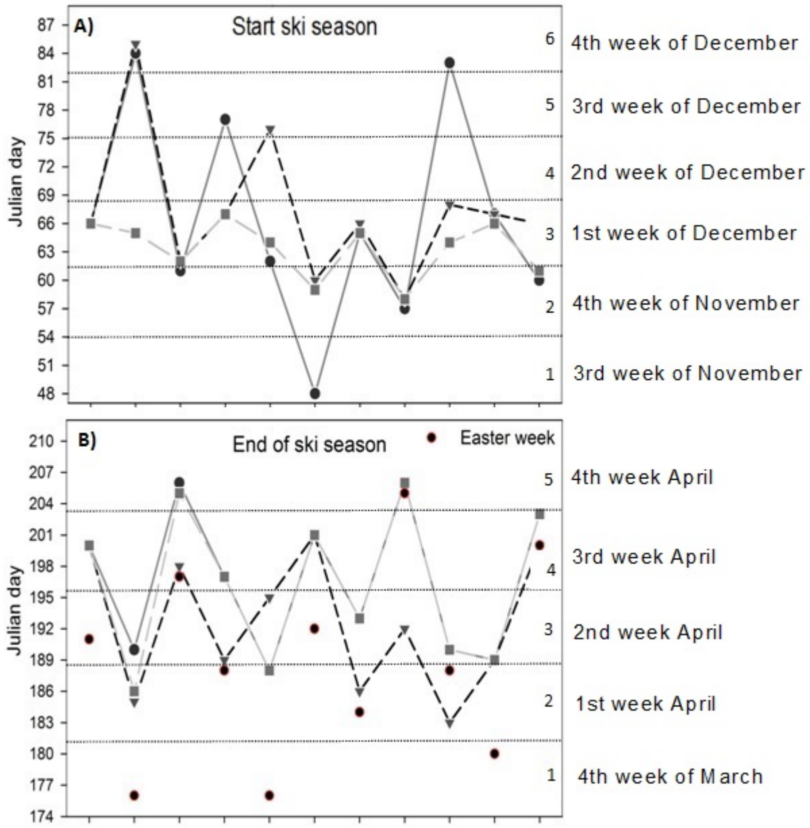


TABLE 2A		
*COD	*AF	*RF
1	1	3%
2	8	24%
3	19	58%
4	0	0%
5	2	6%
6	3	9%

TABLE 2B		
*COD	*AF	*RF
1	2	6%
2	10	30%
3	7	22%
4	10	30%
5	4	12%

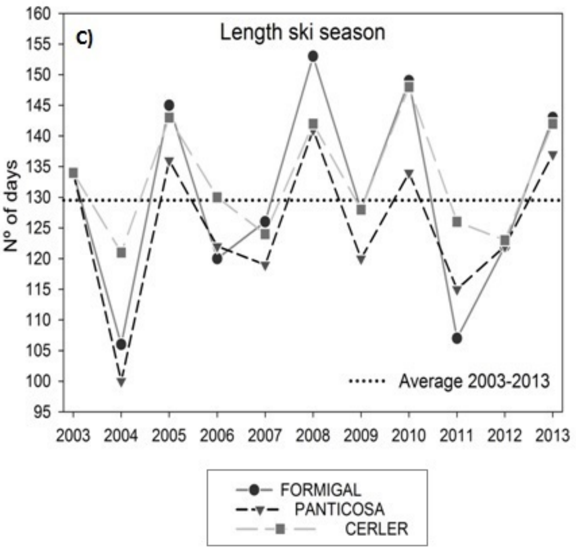


Table 2C					
FORMIGAL		PANTICOSA		CERLER	
Nº days	*AF	Nº days	*AF	Nº days	*AF
100-120	3	100-120	5	100-120	0
121-140	4	121-140	5	121-140	7
141-160	4	141-160	1	141-160	4

Figure 2: Dates of the ski season from 2003 to 2013. A) Start date; B) End date; C) Ski season length. The ordinate in A) and B) indicates Julian days after October 1, and the ordinate in C indicates total number of days.

Table 2**:** Absolute frequency (AF) and relative frequency (RF) of the A) start of ski season; B) end of ski season; and C) ski season length.

*Codes 1 to 6 in Table A and codes 1-5 in Table B indicate the number of week.

3.3.4.1.2 Frequency of closure dates and their causes

During all 11 ski seasons and for all 3 stations, there were several days in which it was not possible to open (Figure 3.1), but there were large differences in the number of closed days among years and stations. Panticosa had the largest number of closure dates, as well as the largest inter-annual variability in closure (8-28 days per year), followed by Formigal (1-13 days per year), and Cerler (1-8 days per year). Figures 3.2 A-C show the reasons for closure at the three ski stations, as a percentage of the average, for three ski seasons (2011-2012, 2012-2013, and 2013-2014). The main reasons for closing the Panticosa station was lack of snow (53%) and excessive wind (23%); the lack of snow at this station is because it is at a lower elevation than the other two stations. In Formigal, 63% of closures were due to heavy snowfall, followed by excessive wind (25%). In Cerler, excessive wind was the main reason for closing (86%).

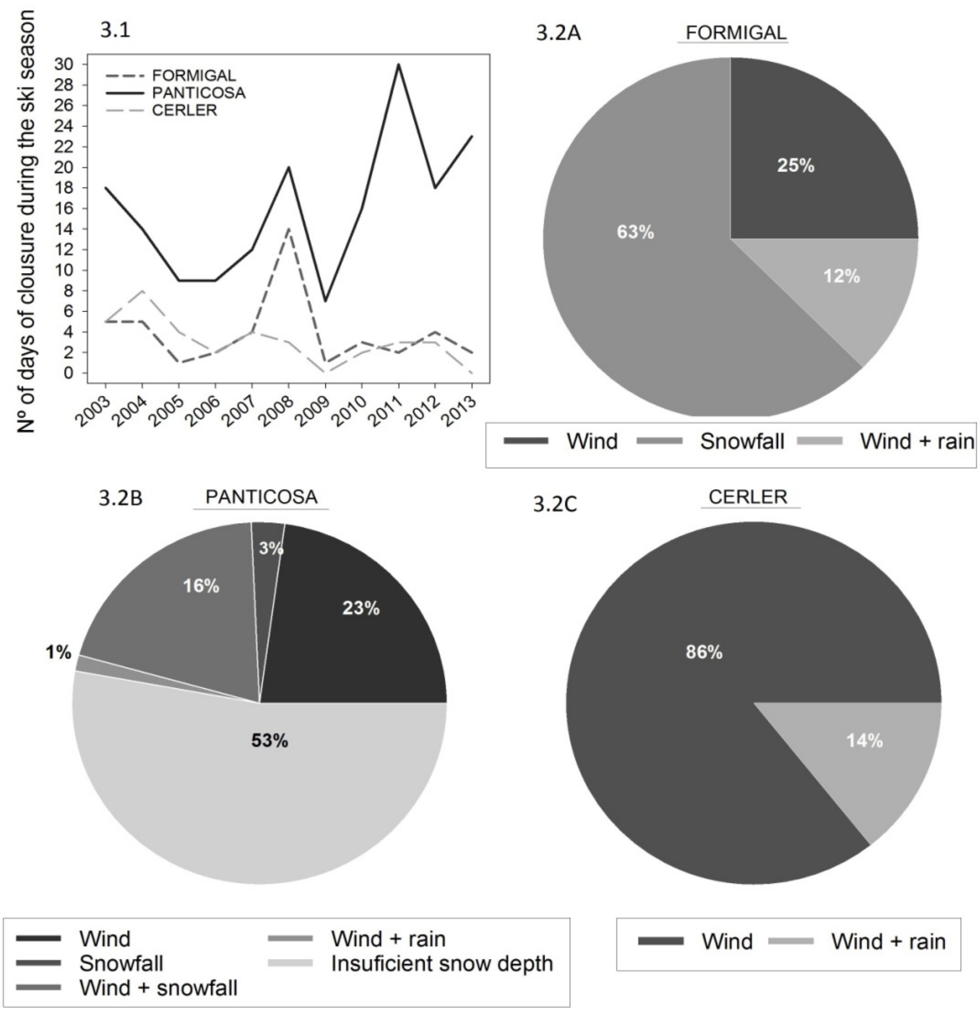


Figure 3**:** Frequency and reasons for closure of ski stations. 3.1) Number of closed days per season at each ski station from 2003-2013. 3.2A-C) Motives for closure of each ski station (pooled data from 2011-2013).

3.3.4.2 Temporal patterns of attendance

Figure 4A shows the total number of skiers at the three ski stations during the study period. This figure shows a trend towards increasing number of skiers since 2007. Three seasons stand out above the others (2007-2006, 2008-2009, and 2009-2010), followed by a decrease in the following years. The average number of skiers per season was 459.000 at Formigal, 265.000 at Cerler, and 91.000 at Panticosa. The peak years had 615.000 skiers at Formigal, 116.000 at Panticosa, and 323.000 at Cerler.

Figure 4B shows the distribution of monthly demand in absolute numbers, and Table 3 shows the monthly percentages at each ski stations by month. February had the highest attendance (27.7% for all 3 ski stations), followed by January (25.6%) and March (24%). April also had many skiers when the Easter holiday was in that month.

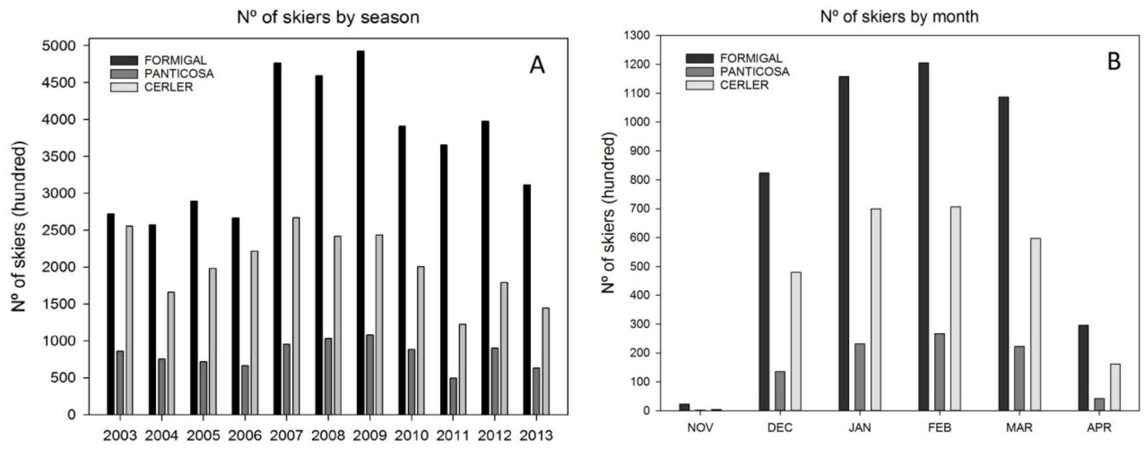


Figure 4: Attendance at each ski station. 4A) Total attendance at each ski station from 2003-2013; 4B) Skiers per month at each ski station (pooled data from 2003-2013).

MONTH	FORMIGAL	PANTICOSA	CERLER
November	1%	0%	0%
December	18%	15%	18%
January	25%	26%	26%
February	26%	30%	27%
March	24%	25%	23%
April	6%	4%	6%

Table 3: Percentage of skiers at each ski station from November to April (pooled data from 2003-2013).

Figure 5 shows the average cumulative distribution of skiers over time at each ski station during the study period, and Table 4 shows the percentage of skiers accumulated in certain percentage of accumulated days along the ski season. The 5 days with the greatest attendance accounted for 13% of all skiers on average; and the 10, 25, and 50 days with greatest attendance accounted for 23.6%, 52%, and 74.3% of all skiers, respectively. These data show that there is a high concentration of demand at certain times of the season. Figure

5 show that Panticosa had the highest concentration of skiers within a 50 day period (87%), followed by Formigal (74%) and Cerler 71%). In general, the concentration of skiers at each station had low inter-annual variability, with rather similar values throughout the 2003-2013 study period.

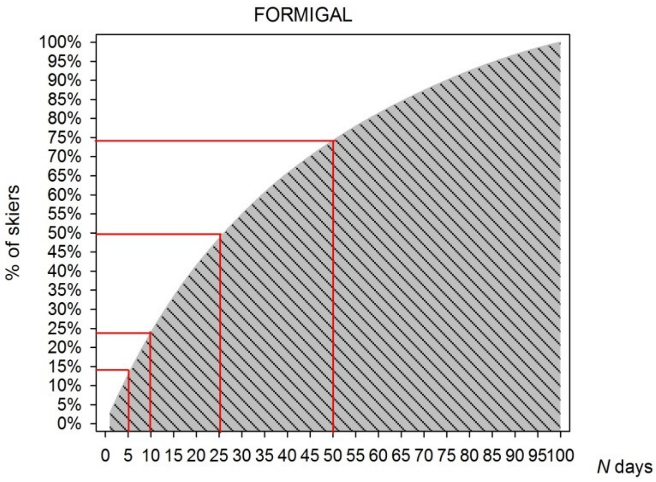


Table 4A	% of skiers			
Ski season	5	10	25	50
2003	13%	24%	48%	74%
2004	15%	27%	54%	79%
2005	13%	23%	47%	71%
2006	14%	26%	52%	77%
2007	11%	21%	44%	70%
2008	11%	21%	46%	72%
2009	10%	20%	44%	70%
2010	12%	23%	49%	75%
2011	15%	26%	52%	78%
2012	14%	26%	49%	75%
AVERAGE	**13%**	**24%**	**49%**	**74%**

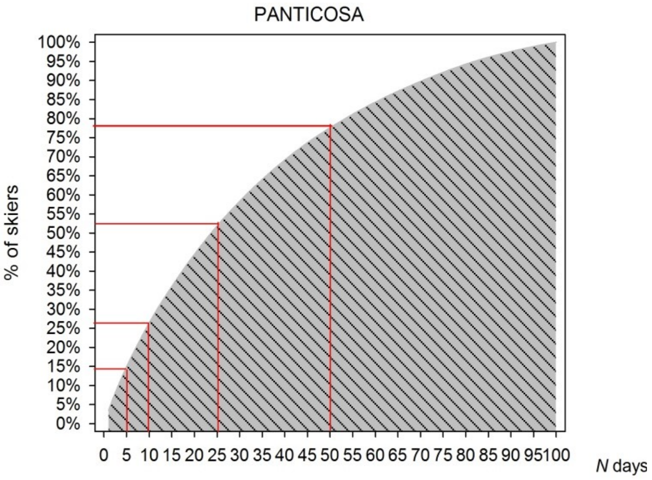


Table 4B	% of skiers			
Ski season	5	10	25	50
2003	14%	25%	49%	75%
2004	18%	33%	58%	82%
2005	14%	24%	47%	72%
2006	14%	25%	51%	77%
2007	12%	23%	49%	76%
2008	13%	25%	51%	78%
2009	13%	24%	48%	76%
2010	14%	26%	54%	79%
2011	21%	34%	61%	85%
2012	15%	26%	50%	76%
AVERAGE	**15%**	**26%**	**52%**	**78%**

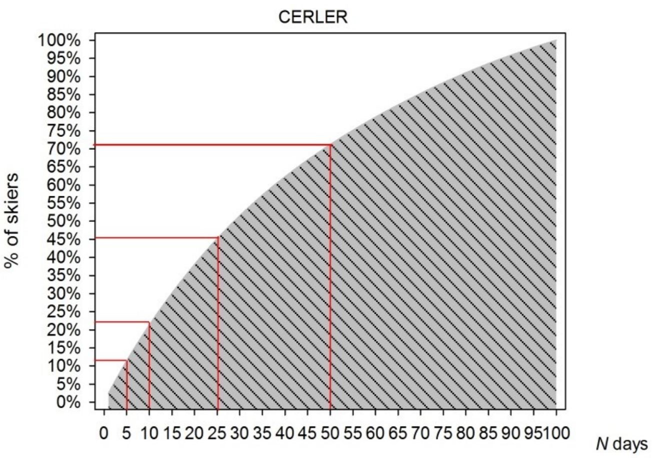


Table 4C	% of skiers			
Ski season	5	10	25	50
2003	10%	19%	41%	67%
2004	11%	22%	45%	72%
2005	11%	20%	42%	67%
2006	11%	20%	45%	71%
2007	10%	20%	43%	70%
2008	12%	22%	46%	72%
2009	11%	20%	44%	72%
2010	12%	23%	49%	74%
2011	14%	24%	49%	74%
2012	13%	24%	49%	73%
AVERAGE	**11%**	**21%**	**45%**	**71%**

Figure 5: Cumulative distribution of skiers at the different ski stations (pooled data from 2003-2013). The abscissa represents the 100 days with the most skiers and the ordinate represents the percentage of skiers accumulated in *N* days. Lines in red data analyzed in the adjacent tables.

Tables 4: Cumulative percentages of skiers at each ski station from 2003-2013.

The inflow of skiers during different festivities is analyzed in more detail below.The left side of Figure 6 shows the percentage of skiers at each ski station and each ski season at the five principal holiday periods (December 6 and 8, winter holidays, March 5, March 19 [Father's day], and Easter week), as well as weekends and weekdays. The bars in the center show the averages over the 11 year study period. The average number of holiday skiers was greatest at Cerler (26.1%), followed by Panticosa (25.2%) and Formigal (24.5%). The average percentages for weekday skiers (Monday-Friday) were 40.3% (Panticosa), 39.4% (Formigal) and 34.4% (Cerler). The average percentages for weekend skiing (Saturday and Sunday) were 39.5% (Cerler), 36.10% (Formigal) and 34.5% (Panticosa). Notably, the percentage of skiers during the 2-day weekend was similar to the percentage during all 5 weekdays.

The right side of Figure 6 details the attendance during the 5 major holiday periods. The Christmas holidays attracted the most skiers, and accounted for 48% to 80% of all holiday skiers and about 16% of skiers throughout the year. Easter week accounted for 5% to 45% of all holiday skiers; this great variability is because Easter week sometimes occurs in the late ski season. In some cases, the December 6 and 8 holidays can be linked to a weekend, leading to a 4-day or even a week-long holiday. This is an important date, because it marks the start of the ski season. Although many ski stations open on this long weekend, they may later have to close due to the lack of snow or high temperatures. As the different holidays have different durations, Table 5 shows the number of skiers per day on the 5 different holidays. Table 5 shows that an isolated day, such as March 19 (Father's Day in Spain), has about 6000 skiers per day at Formigal, and is also the most popular day at Panticosa, and the second most-popular day at Cerler.

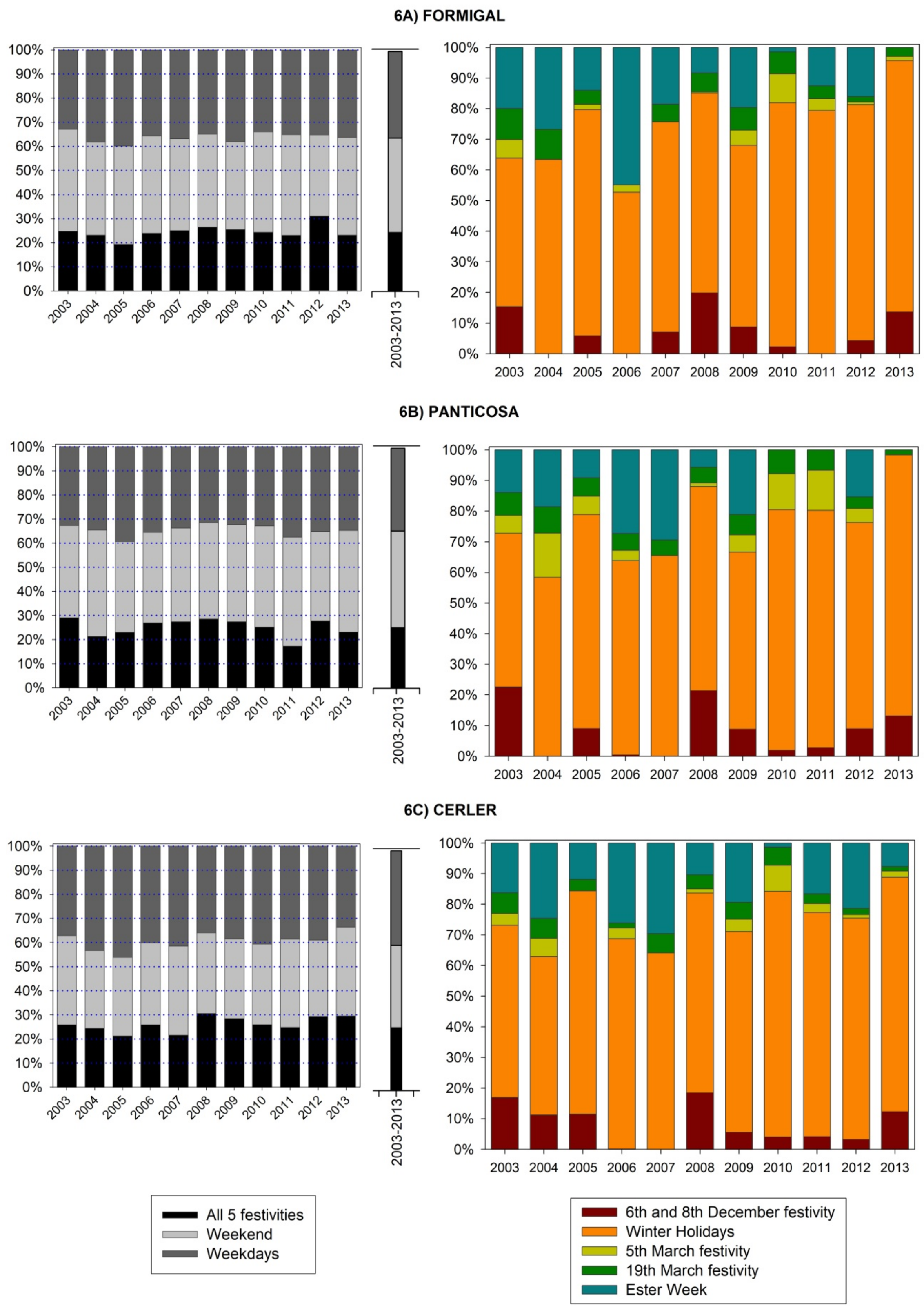


Figure 6: Attendance of skiers at the different ski stations on holidays, weekends, and weekdays. Figures on the left show attendance on the 5 aggregated major holidays, weekend days, and weekdays from 2003-2013. Center bar show pooled data from 2003-2013. Figures on the right show disaggregated data for each of the 5 major holidays from 2003-2013.

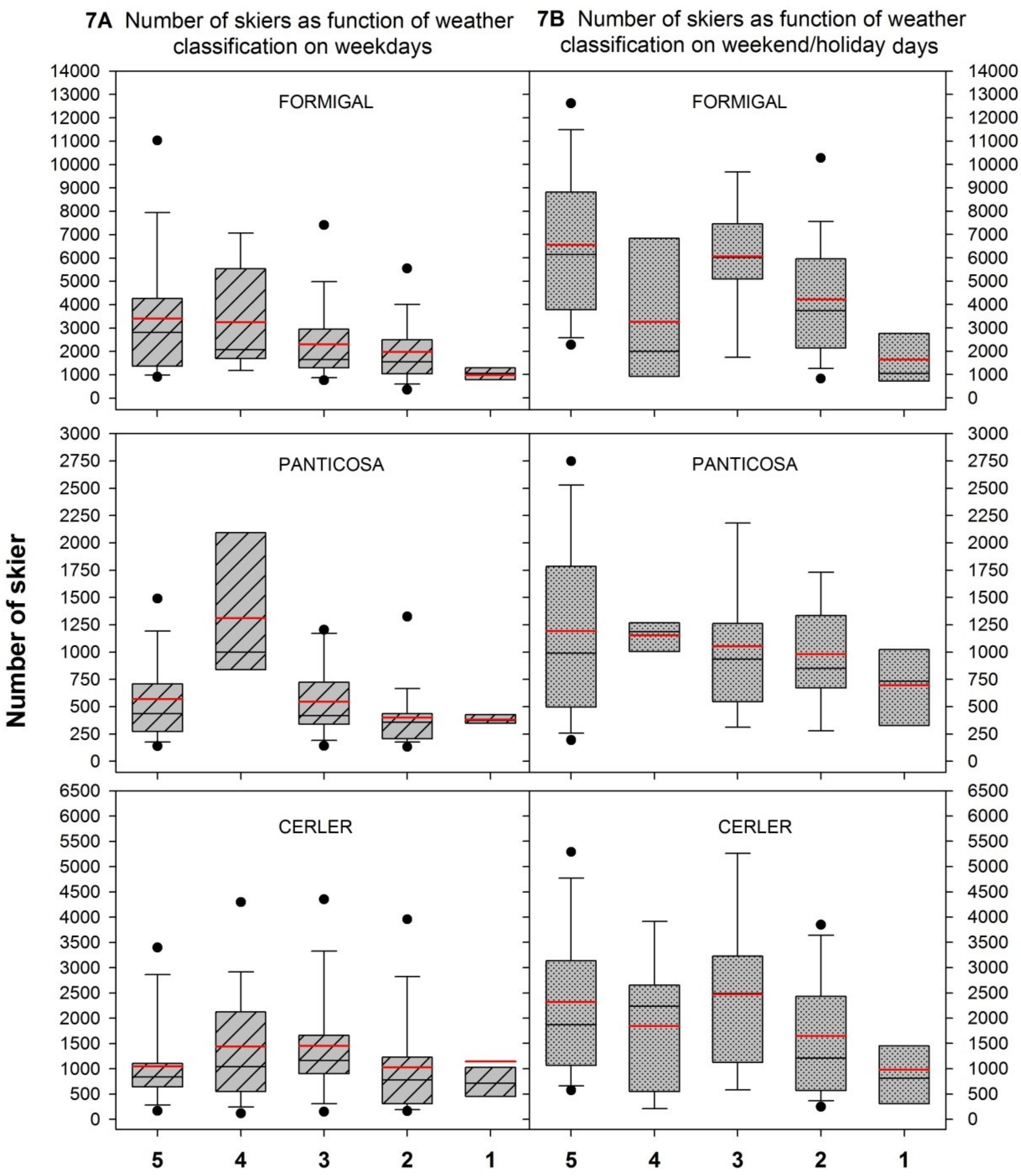
	6th and 8th December festivity	Winter holidays (24D-6J)	5th March festivity	19th March festivity	Easter Week
FORMIGAL	3619	5579	3283	6188	4681
PANTICOSA	852	1099	1191	1361	803
CERLER	2313	3437	2107	3043	2785

Table 5: Average number of skiers per day on the different holidays at the three ski stations (pooled data from 2003-2013).

3.3.4.3 Relationship of attendance with weather and number of ski runs

3.3.4.3.1 Attendance and weather

We analyzed the effect of weather conditions on attendance on weekdays (Figure 7A) and on weekends and holidays (Figure 7B) at the 3 ski stations. Table 6 shows the average attendance for 5 different types of weather conditions. On weekdays, Formigal had significantly more skiers when the weather was sunny or partly cloudy (type 5; 3286 skiers) than on windy days without precipitation (type 2; 1973 skiers). On weekdays, Panticosa also had significantly more skiers on days with no precipitation (type 4; 1467 skiers) than on days with wind and precipitation (Type 1; 384 skiers). There was no significant effect of weather conditions on attendance at Cerler on weekdays. During the weekend, weather only had a significant effect at Formigal; the greatest difference was between sunny or partly cloudy days (Type 5; 6554 skiers) and windy days with precipitation (Type 1; 1639 skiers). (See Table 1 of supplementary material).



Legend of X axis of figure 7 and tables 5 and 6.		
Code	Weather description	Symbol
5	Sunny or partly covered	
4	Covered without precipitation	
3	Covered with liquid or solid precipitation	
2	Windy day but sunny or partly covered	
1	Windy day with liquid or solid precipitation	

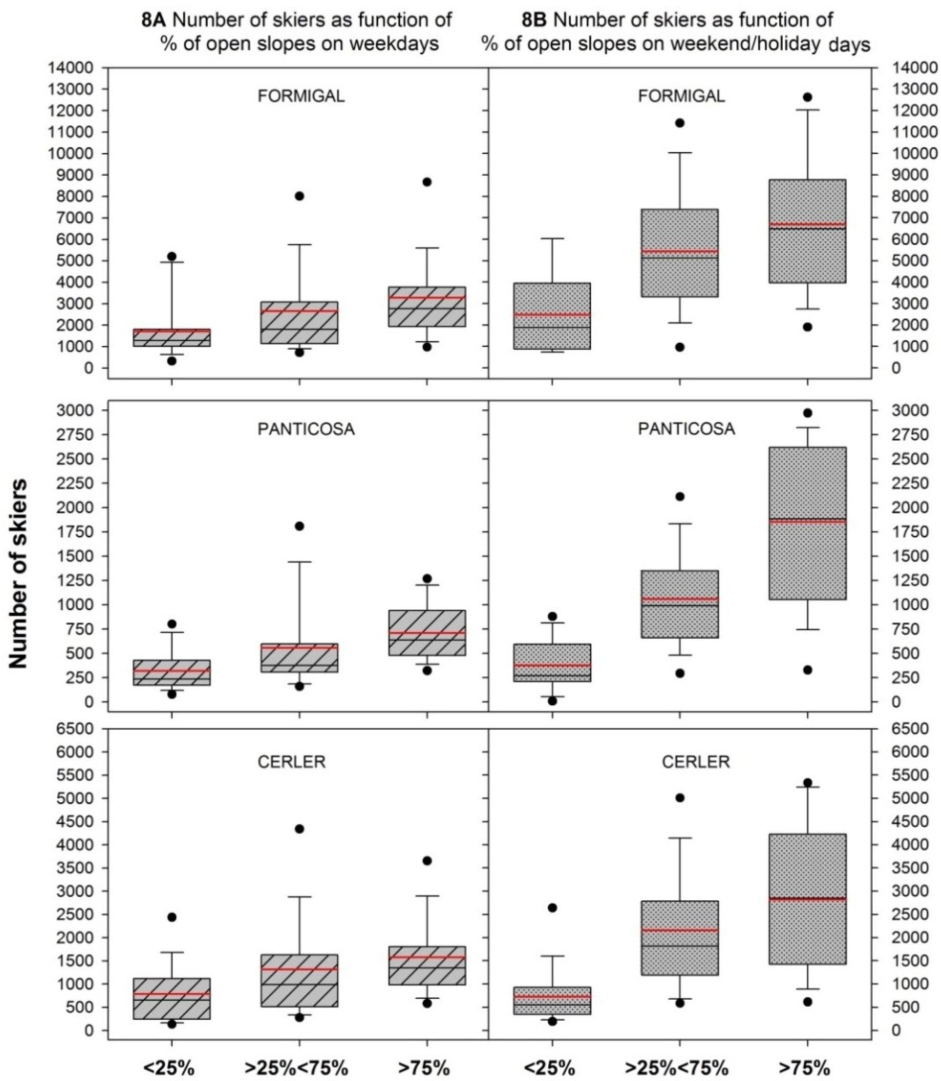
Figure 7A and 7B: Number of skiers at each ski station during different weather conditions (pooled data from 2011-2013). Figures on the left show attendance as function of weather on weekdays. Figures on the right show attendance as function of weather on weekends and holidays. Red line: average, black dot: 5th and 95th percentiles.

FORMIGAL				PANTICOSA				CERLER			
Weekdays		Weekend/Holidays		Weekdays		Weekend/Holidays		Weekdays		Weekend/Holidays	
5	3286	**5**	6554	**5**	568	**5**	1191	**5**	1318	**5**	2321
4	3243	**4**	3880	**4**	1467	**4**	1153	**4**	1438	**4**	1845
3	2298	**3**	6053	**3**	545	**3**	1053	**3**	1454	**3**	2474
2	1973	**2**	4218	**2**	399	**2**	981	**2**	1027	**2**	1648
1	990	**1**	1639	**1**	384	**1**	695	**1**	1148	**1**	984

Table 6: Number of skiers/day on weekdays and weekends/holidays and type of weather (1-5, as shown in Fig. 7) at the three ski stations (pooled data from 2011-2013).

3.3.4.3.2 Attendance and number of open ski runs

We also analyzed effect of the percentage of open ski runs on skier's attendance. Table 7 shows the relationship of these variables, in which we categorized the number of open ski runs into three levels (<25%, 25%-75%, and >75%). During weekdays, attendance was twice as high when more than 75% of the runs were open relative to fewer than 25% of runs were open (with about 48%, 55%, and 50% fewer skiers in Formigal, Panticosa, and Cerler, respectively). During the weekend and holidays there was only a significant difference in ski attendance between <25% open and >75% open (except in Cerler where there is also great differences between <25% and 25%-75%). This means that the difference in the number of skiers when fewer than 25% of trails are open and when more than 75% are open is the triple, with percentage of less skiers about -63%, -80% and -74% in Formigal, Panticosa and Cerler respectively when only 25% are open. (See Table 2 of supplementary material).



Code	Description
1	<25%
2	>25% <75%
3	>75%

Figure 8: Relationship of the number of skiers (ordinate) with the percentage of open ski runs (abscissa). The left panel shows attendance as function of the percentage of open runs on weekdays and the right panel shows attendance as function of the percentage of open ski runs on weekends and holidays. Red line: average, black dots: 5th and 95th percentiles.

FORMIGAL				**PANTICOSA**				**CERLER**			
Weekdays		**Weekend/Holidays**		**Weekdays**		**Weekend/Holidays**		**Weekdays**		**Weekend/Holidays**	
1	1709	**1**	2472	**1**	319	**1**	375	**1**	788	**1**	726
2	2656	**2**	5429	**2**	556	**2**	1060	**2**	1317	**2**	2159
3	3276	**3**	6696	**3**	710	**3**	1851	**3**	1576	**3**	2816

Table 7: Number of skiers per day on weekdays and weekend/ holidays and percentage open ski trails (2011-2013 seasons).

3.3.5 Discussion

This study characterized the attendance at 3 ski stations in the Aragon Pyrenees, and assessed the influence of snow availability (indicated by the percentage of open ski runs) and weather conditions on attendance from 2003-2013. The methodologies used, based on direct statistical relationships, are suitable for sensitive analysis of the influence of different factors on ski stations at a local scale. Analysis of visitation data that is aggregated at a regional or higher level could mask the unique characteristics of different sites, such as the effect of different factors on low-altitude and high-altitude ski stations. Some previous studies showed that skier demand under the same weather or climatic conditions could be very different at nearby ski stations due to differences in geographical and socioeconomic conditions, in that some ski stations could experience decreased attendance while others experience increased attendance during the same season (Pons et al., 2014; 2015). Moreover, pooling data from multiple ski stations could lead to statistically significant correlations, but incongruent conclusions, such as a positive relationship between attendance and cloudiness (Falk, 2013), even though sunny weather increases attendance.

There was a moderate variability in the starting date of ski season (mainly in the last weeks of November and the first week of December) during the study period. Thus, the December 6 and 8 holidays are important for the ski stations and normally open is possible with snowmaking. Moreover, these holyday dates can account for a large share of the total number of skiers during a season. Thus, our finding in the Aragon Pyrenees is congruent with that reported by Elsasser and Bürki (2002) and Falk and Hagsten (2016) for the Alps. These findings indicate that a delayed start of winter may negatively impact overall attendance, because it affects to dates of potential peak affluence and may also affect attendance during the subsequent months.

We observed a much higher variability in closing dates than opening dates, mostly due to variations in the date of Easter week. Most years, snow lasts at the high-elevation ski stations throughout Easter and until early May (Navarro-Serrano and López-Moreno, 2016). Thus, snow availability is not an issue, with the exception of some years at some ski stations such as Panticosa. However after the Easter holiday - or even during the Easter holiday when it occurs in late April - there is a dramatic decrease in the number of skiers. This is typically due to not good quality of snow conditions, and also because of competition with other types of tourism (*i.e.* coastal tourism and other outdoor activities). Falk (2010) reported that an early Easter holiday increased the number of overnight stays by an average of 1.9% in Austria.

The average duration of the ski season at the 3 ski stations we studied was 130 days, exceeding the widely used number of 100 days considered necessary for economic sustainability of a ski station (Witmer, 1986).

The average annual attendance of skiers during the study period at the 3 ski stations was 815.000 and some years had more than 1 million skiers. By far, February and March are the months with the greatest attendance. Our data also shows particularly high attendance on weekends and holidays. Thus, the number of skiers on weekend days and holidays is at least double that of weekdays. In general, about 75% of the attendance occurs on about 50% of the days when the ski stations are open. Shih et al. (2009) reported similar results in Michigan, where 50% of the average daily lift ticket sales occurred on weekends, and 56% of sales occurred on weekends during the off-peak season (November, March, and April). It is noteworthy that a high concentration of skiers on a relatively small number of days can increase the economic vulnerability of ski businesses if these peak dates have poor snow or bad weather conditions (Steiger, 2011).

Poor snow or bad weather conditions can lead to total or partial closure of ski stations. We identified windy conditions as the main cause of total closure of the ski stations, although lack of snow often led to partial closures. Heavy snowfalls were another reason for closure and low attendance during the study period. Our results are in line with findings of Gilbert and Hudson (2000) for Nevada and Englin and Moeltner (2004) for California. We found that the 3 ski stations respond differently to different factors regarding closure, and this is a consequence of their different elevations and different meteorological conditions.

Meteorological factors have the greatest influence on attendance, because of aesthetical factors (sunshine, solar radiation, high visibility, and low cloud cover) and physical factors (wind and rain). In particular, aesthetical factors increase the attractiveness of the ski stations, thus stimulating tourism (De Freitas, 2003). Despite this, we found no significant relationship between the number of skiers and weather on weekends and holidays except in Formigal, where good weather can triple the number of skiers. The lower impact of weather conditions on weekends and holidays is probably because reservations for these times are made days and even weeks in advance, whereas much of the attendance on weekdays is not planned so far in advance. Thus, weekday attendance depended more strongly on weather conditions. It is important to note that windy conditions had the greatest negative impact on all days. In Finland, windy conditions are also the most common reason for closure of ski areas, and rain is also a serious threat, because even a small amount of precipitation increases snow melting and leads to cancellations or bad tourist experiences (Tervo, 2008).

Percentage of open ski runs can also affect the number of skiers, especially on weekends. The attendance was more than 3-fold greater at times when more than 75% of trails were open relative to times when fewer than 25% of trails were open. During the week, the difference is more than double. It is also necessary to consider that attendance on weekends is normally very high, and if a ski station has limited trails for skiing, many skiers will be deterred by the crowds.

3.3.6 Conclusions

This study only examined 3 ski stations in the Pyrenees, and the relatively short study period did not allow analysis of long-term trends. Nonetheless, this is the first study to examine the relationship of the number of skiers in the Pyrenees with snow availability, holiday schedules, and weather conditions. The study period was not long enough to assess effects of climatic changes or socioeconomic factors on attendance. However, we objectively reported the current patterns and factors governing the daily and inter-annual variability of attendance at 3 ski stations in the Pyrenees. This information can provide a basis for evaluation of the vulnerability of the ski industry in the future, under different climate change scenarios, and the different impacts of good and poor-snow conditions. Is very important for these businesses to know how skiers may respond to adverse snow and weather conditions. Our analysis of seasonal, monthly, daily, and holiday attendance at ski stations contributes to a better understanding of the reasons for variations in attendance at Pyrenean ski stations.

The information reported here provides a foundation for understanding the effect of climate variability and climate change on the demand-side of the skiing industry. Some previous studies examined the demand at ski regions throughout the world (Falk, 2013; Rutty et al., 2015; Shih et al., 2009). However, there are significant regional differences in the sensitivity to the different factors that govern demand, and there are also regional differences in holidays, so these ski stations may have different vulnerabilities to future climate changes. We examined factors specific for 3 ski stations in the Pyrenees, so our data can be used for future analogue studies that analyze the impact of climate change in this region.

It would be interesting to complement the results of the present study with a survey of skiers and their attitudes and behaviors.

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Supplementary material:

ANOVA AND POST HOC TEST FORMIGAL WD					
F = 5.165	Sig= 0.001				
	1	2	3	4	5
1					
2	1,000				
3	1,000	1,000			
4	0,352	1,000	1,000		
5	0,043	0,004	0,512	1,000	

ANOVA AND POST HOC TEST FORMIGAL WE					
F = 5.770	Sig= 0.000				
	1	2	3	4	5
1					
2	0,619				
3	0,048	0,939			
4	1,000	1,000	1,000		
5	0,002	0,013	1,000	1,000	

ANOVA AND POST HOC TEST PANTICOSA WD					
F = 3.954	Sig= 0.004				
	1	2	3	4	5
1					
2	1,000				
3	1,000	1,000			
4	0,030	0,003	0,024		
5	1,000	0,430	1,000	0,017	

ANOVA AND POST HOC TEST PANTICOSA WE					
F = 0.691	Sig= 0.600				
	1	2	3	4	5
1					
2	1,000				
3	1,000	1,000			
4	1,000	1,000	1,000		
5	1,000	1,000	1,000	1,000	

ANOVA AND POST HOC TEST CERLER WD					
F = 0.735	Sig= 0.569				
	1	2	3	4	5
1					
2	1,000				
3	1,000	1,000			
4	1,000	1,000	1,000		
5	1,000	1,000	1,000	1,000	

ANOVA AND POST HOC TEST CERLER WE					
F = 2.142	Sig= 0.080				
	1	2	3	4	5
1					
2	1,000				
3	0,361	1,000			
4	1,000	1,000	1,000		
5	0,309	0,724	1,000	1,000	

Table 1: ANOVA and post hoc tests of the effect of different weather types (1-5, see Fig. 7) on attendance on week days (WD) and weekend days (WE) at the 3 ski stations.
F: one-factor ANOVA; Sig: significance, in which a value below 0.05 indicates rejection of the hypothesis that the means are equal.

ANOVA AND POST HOC TEST FORMIGAL WD					
F	sig		1	2	3
5.159	0.006	1			
		2	0,183		
		3	0,007	0,159	

ANOVA AND POST HOC TEST FORMIGAL WE					
F	sig		1	2	3
9.350	0.000	1			
		2	0,009		
		3	0,000	0,142	

ANOVA AND POST-HOC TEST PANTICOSA WD					
F	sig		1	2	3
10.487	0.000	1			
		2	0,007		
		3	0,000	0,085	

ANOVA AND POST-HOC TEST PANTICOSA WE					
F	sig		1	2	3
32.401	0.000	1			
		2	0,000		
		3	0,000	0,000	

ANOVA AND POST-HOC TEST CERLER WD					
F	sig		1	2	3
10,256	0,000	1			
		2	0,001		
		3	0,000	0,174	

ANOVA AND POST-HOC TEST CERLER WE					
F	sig		1	2	3
16,489	0,000	1			
		2	0,000		
		3	0,000	0,075	

Table 2: ANOVA and post hoc tests of the effect of the number of open trails (1: <25%, 2: 25-75%, 3: >75%) on attendance on week days (WD) and weekend days (WE) at the 3 ski stations. F: one factor ANOVA; Sig: significance, in which a value below 0.05 indicates rejection of the hypothesis that the means are equal.

3.4 SKIER DEMAND AND BEHAVIOURAL ADAPTATION TO WEATHER AND CLIMATE CHANGE IN CENTRAL PYRENEES

Abstract

In this study we used surveys methodology to know how skiing tourists perceive weather and climate change, and their behaviour concerning ski practice in a large region of the Spanish Pyrenees. A novel mixed system was used to collect the surveys; *in situ* and online (n=205). The majority of respondents were in the age group 26 to 54 years, with a mean age of 35.4. Most respondents (80.5%) did not have a season pass, and the average number of times respondents went skiing during a season was 13 days. Regarding climate preferences, 80% of the skiers reported that they did not go skiing on a rainy day, 58.5% did not go to ski on a day of excessive wind, 46% when there was poor visibility, and 41% did not go skiing in marginal snow conditions. A total of 91% of respondents reported having been affected by snow shortages during a ski season in their usual place. Regarding adaptation behavioural, 49% of respondents would continue skiing less often but whenever possible in their usual place, 21% skied in the usual way even with bad snow conditions, 10% replaced skiing or snowboarding with another mountain activity (hiking, mountain cycling, etc.), 10% travelled farther to find good snow conditions, and 8% stopped skiing during that season. A total of 77% of the respondents believed that climate change has a medium or high impact on snow conditions in the Pyrenees, but only 48% think that climate change has already affected winter tourism, and 76% consider that this is a problem to be faced in the future.

KEYWORDS: Survey, Skiers, Pyrenees, Weather, Climate change, Adaptation.

3.4.1 Introduction

The tourism industry is highly linked to the natural environment, and it is an economic activity highly vulnerable to varying and changing weather and climate conditions. In particular, winter tourism activities are often dependent on elements such as sufficient snowpack, the possibility of snowmaking, precipitation, good visibility, etc. (Gössling et al., 2012; Scott, Gössling and Hall, 2012). Therefore, the winter sports sector is expected to be particularly vulnerable to changing climate conditions (Scott, Dawson and Jones, 2008; Puetz et al., 2011; Soboll and Dingeldey, 2012). There is relatively abundant literature that relate climate change with ski tourism from the point of view of offer. Much of this literature is reviewed in Gilaberte-Búrdalo et al., 2014). This literature has mainly focused on the vulnerability of the international ski industry due to the impact of increased average temperatures on snow quantity and quality for ski areas. These studies have consistently found the ski industry to be at risk to climate change, with a continued reduction in the number of operating ski areas or the additional need for artificial snowmaking technologies. In the majority of the analysed places, seasons are projected to become shorter on average and more variable due to a decrease in natural snow cover, which is expected to cause a decline in the number of visitors, mainly at low-altitude and low-latitude ski resorts.

Comparatively, there are fewer studies with respect to the influence of weather and climate on skier demand, including tourist behavioural responses to past or projected climatic variability, poor snow conditions, and ski resort closures. This gap is surprising, as it is the preferences of the skiers for ski destinations that will ultimately determine a destinations' future prospects (Elsasser and Messerli, 2001; Englin and Moeltner, 2004; Fukushima et al., 2002; Pickering, Castley and Burtt 2010; Shih, Nicholls and Holecek, 2009; Toglhofer, Eigner and Prettenthaler, 2011).

Within the studies that analyse the response of the tourists or skiers to environmental changes or simply to the interannual climatic variability are those that use the methodology of surveys or questionnaires. König (1998) examined how skiers in Australia might respond to hypothetically poor snow conditions expected in the future. 25% of respondents indicated they would continue skiing at the same place and frequency, 31% would ski less often, 38% would ski at another location and 6% would quit skiing. Similar surveys were also conducted by Behringer, Bürki and Fuhrer (2000) and Elsasser and Bürki (2002) at resorts in Switzerland. The two studies reached very similar results. Behringer et al. (2000) found that 30% of respondents would not change their skiing behaviour, 11% would ski at the same location but less often, 28% would ski at a more snow-reliable resort at the same frequency, and 4% would give up skiing. Elsasser and Bürki (2002) found that the majority of skiers would ski at the same frequency (30% at the same resort, 28% at another snow-reliable resort), 32% would ski less often and 4% would stop skiing. Behringer et al. (2000) also examined the perceptions of tourists on the topic of climate change and the manner in which they might adapt their behaviours: they surveyed skiers and snowboarders in Switzerland and found that 83% of respondents believed that climate change would threaten ski tourism and almost half believed that this would occur between the year 2000 and 2030. Unbehaun, Pröbstl and Haider (2008) examined how climate change impacts may affect winter sports tourists, in terms of their activity levels as well as destination choice. When provided with scenarios of consecutive winters with snow deficiency, 68% of winter tourists would give up destination loyalty in favour of a more snow-secure destination. Pickering et al. (2010) evaluated the attitudes towards climate change in the largest ski resort in Australia in 2007 using 351 questionnaires. The results showed that 90% of skiers would ski less often in the case of five consecutive snow poor years. The majority of respondents (78%) believed global warming will have an adverse effect on the Australian ski industry. Vivian (2011) obtained that the main factors that were found to have a strong influence when choosing a ski resort are the quality of snow conditions, the absence of crowded slopes and close proximity to their place of residence. Respondents were also asked about the importance of various weather aspects as well as ideal conditions to ski. It was found that the absence of rain was the most influential weather factor out of the six presented in this study for 66% of respondents. The second most important weather factor was having good visibility (61% of all respondents), followed by the absence of strong winds. Furthermore, 87% would ski their usual frequency, with a lower total number of days, 11% would ski more often than normal to make up for a shorter season, and 1% would stop skiing for the entire winter. Dawson, Scott and Havitz (2013) asked skiers about how they behaved during seasons with bad snow conditions in the US Northeast. 38% of respondents indicated that they skied less often at some point in past seasons, which is only slightly higher than those who say that they intend to ski less often in the future (34%). When considering spatial substitution in past seasons with poor snow conditions, 60% of the individuals in this study indicated having at some point travelled elsewhere in the US Northeast to ski, and 67% had travelled outside of the region. Rutty et al. (2015) examined how skiers in Ontario (Canada) would change their participation patterns if their preferred ski resort were closed due to a lack of snow. The survey focuses on current behavioural responses, rather than decisions based on future scenarios of climate change. The results also indicate that beginner and infrequent skiers, as well as parents with children enrolled in ski lessons, were more likely to either ski less and/or stop skiing altogether, while experienced and core skiers were more likely to engage in spatial substitution. The largest share of respondents (48%) stated that they would engage in spatial substitution by skiing as often as they currently do, but at other locations until their resort opened. Almost half of the respondents would engage in temporal substitution, with 31% opting to ski less often and wait for the resort to open and 12% who would wait for their resort to open and ski more frequently in the shortened season. Steiger, Peters and Abegg, (2015) conducted a skier survey at the end of the 2013/14 winter season in 22 ski areas in Western Austria, Southern Germany, and Northern Italy. Snow quality and snow reliability were rated as the most important factors for destination choice followed for the number of skiing days per season, good weather. When asked if certain weather conditions prevent respondents from going skiing, rain was rated the most important, followed by strong winds and fog.

Little is known about the perception and behaviour of the skiers of the Pyrenees to climate change, particularly in relation to how skiers may alter their behaviour in response to climate change. In fact, to our knowledge, there is only one study about the perception of the effects of climate change in winter tourist areas of the Catalan Pyrenees (March, Sauri and Llurdes, 2014) but that does not address in any case the behavior of the tourist in front of different climatic conditions. This study observed that the employment situation was a significant variable, with students, members of large households and the unemployed agreeing more that climate change would bring less precipitation. Age was significant, with young people and respondents with lower incomes being significantly more concerned about the negative effects of climate change on tourism employment in the area, on tourist infrastructure and in more general terms on its negative economic effects.

The aim of the current study is to explore the following questions using online and on-site surveys: (1) how do snow and climate conditions affect the choice of a given ski day in the Pyrenees? (2) How do skiers react to bad weather or snow conditions in terms of frequency of skiing days or substitution of the original destination choice? (3) How does the perception of skiers change regarding present and future climate in the Pyrenees? (4) Do the different groups of skiers (age, expertise, times of practice) influence different behaviors to face weather and snow variability and climate change?

3.4.2 Methods

3.4.2.1 Study area

The Pyrenees is a mountain range located in the northeast of the Iberian Peninsula, bounded by the Mediterranean Sea to the east and the Atlantic Ocean to the west. The Pyrenees extends over 425 km from west to east and constitutes a natural border between Spain and France. The width (north–south) in the central part of the range is 150 km, and declines towards the west and east (López-Moreno and García-Ruiz, 2004). In the Pyrenees the lowest elevations for ski slopes typically range from 1500 to 1700 m a.s.l.: only 30% of them have skiable areas above 2500 m, with 2800 m being the maximum (Gilaberte et al., 2017). During the last season (2016–2017), the Catalan Pyrenees received approximately 1.4 million skiers, Andorra received 2 million and the Aragonese Pyrenees received almost 1.5 million. In all cases, the average number of tourists in the season surpassed the average number of the last years with an increase of around 10–20% (ATUDEM, 2017). The classic ski season in the Pyrenees runs from December to April.

3.4.2.2 Survey design and distribution

The design of the survey and the methodology has been developed following, in part, the methodology of Vivian (2011), Dawson et al. (2013), Rutty et al. (2015) and Steiger et al. (2015). The survey was structured in four sections: the first corresponds to the basic data of the respondent as well as the demographic profile; the second corresponds to the respondent’s sports habits, in terms of the specific modality of skiing and the annual frequency of their practice; section 3 deals with the influence of weather and snow conditions on ski attendance; and section 4 asks tourists about their perception of climate change and how they respond to adverse climatic and snow conditions. The total number of questions in the survey was 18. We used a multiple choice response because it is an efficient and effective measurement (Behringer et al., 2000). Table 1 summarizes the questions that were distributed. The surveys were distributed during two non-consecutive ski seasons; 2014–2015 and 2016–2017. To collect the surveys, a double methodology has been used: the first involved distributing the surveys online to different ski and alpine clubs and the second involved distributing surveys *in situ* in ski resorts in three different locations. The interviewer approached everyone but only distributed the surveys to those who were an adult (18 years and older), had participated in skiing or snowboarding activities during that day and were willing to complete the survey. We compiled 205 valid surveys. We think that the mixed data collection system is the most adequate to avoid some biases such as influencing the respondents' responses to the meteorological weather that they make on the day of the survey.

SECTION 1: DEMOGRAPHIC PROFILE
1. Age
2. Sex
3. Place of origin
SECTION 2: SPORTS HABITS
4. Typology of skiing
5. Years of practice
6. Frequency of practice during a ski season
7. Possession of season pass
SECTION 3: INFLUENCE OF METEOROLOGY AND NIVOLOGY
8. Importance that the respondents gives to meteorological and nivological conditions.
9. In which of the following (meteorological) situations would the respondent not go skiing.
10. The respondent has been affected by bad snow conditions in the last 10 years.
11. How they have adapted in a situation of snow shortage.
SECTION 4: PERCEPTION OF CLIMATE CHANGE AND ADAPTATION RESPONSES
12. Do you think that climate change affects the Pyrenees actually?
13. Do you think that climate change affects winter tourism in the Pyrenees actually?
14. Do you think that climate change will affect winter tourism in the Pyrenees?
15. What meteorological and nivological conditions do you believe will affect climate change?
16. If the station where you usually go presents bad snow conditions, would you pay more money to move to a station farther away to look for optimal conditions?
17. Would you be willing to pay a higher price for the ski pass at the stations you usually go to in order to compensate the resort for providing artificial snowmaking
18. If you could not ski/snowboarding as often as you currently do, what other mountain sports activities would you do?

Table 1: Questions distributed to the skiers.

3.4.2.3 Data analysis

Descriptive analysis and graphical representation of the results was carried out for the four sections of the questionnaire. In addition, we used analysis of variance (ANOVA) to determine whether statistically significant differences in the means exist between different groups of skiers. An F-test was used to determine the significance of differences. When mean values are equal, F has a value of 1; if they differ, F has a value greater than 1. The value of the F statistic is presented with its level of significance (p-value.). A p-value below 0.05 led to rejection of the assumption of similar means (Rubio-Hurtado and Berlanga-Silvente, 2012).

3.4.3. Results

3.4.3.1. Demographic profile

In this section, the demographic profile of the respondents was analysed (Figure 1). In the sample of surveys, 19.5% were female and 80.5% were male. Most of the respondents came from the community of Aragon, 33.5%, 17.5% Madrid, 14% País Vasco, 13.5% Cataluña and 7.5% from Navarra. All these regions are part or in the proximity of the Pyrenees, except Madrid. 14% came from other regions. The average age of respondents was 35.4 years, with the age group between 26 and 45 years being 54% of the total sample, followed by the 18–25 age group (23%). No response was obtained from skiers above 65 years.

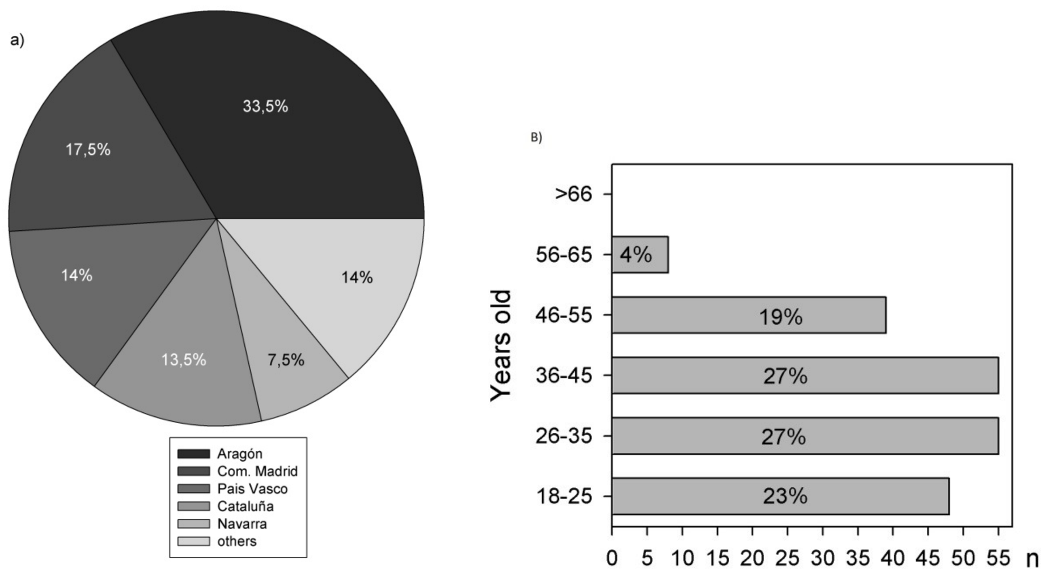

Figure 1: Demographic profile: a) Origin place b) age.
X axis number of respondents

3.4.3.2 Sports habits

In terms of typology of skiing in ski resorts, Figure 2a shows that most of them (65%) were alpine skiers, 18% were snowboarders, 12% were mixed alpine skiing and snowboarding and a minority were mountain skiers (5%). Regarding the years of experience, we found that the majority of skiers who responded had long experience of skiing, with 63% of the people having more than 10 years of experience. For season passes, 80.5% of the respondents did not have a season pass, and the average annual number of skiing days was 13.2, although most people (61%) skied 1 to 10 times.

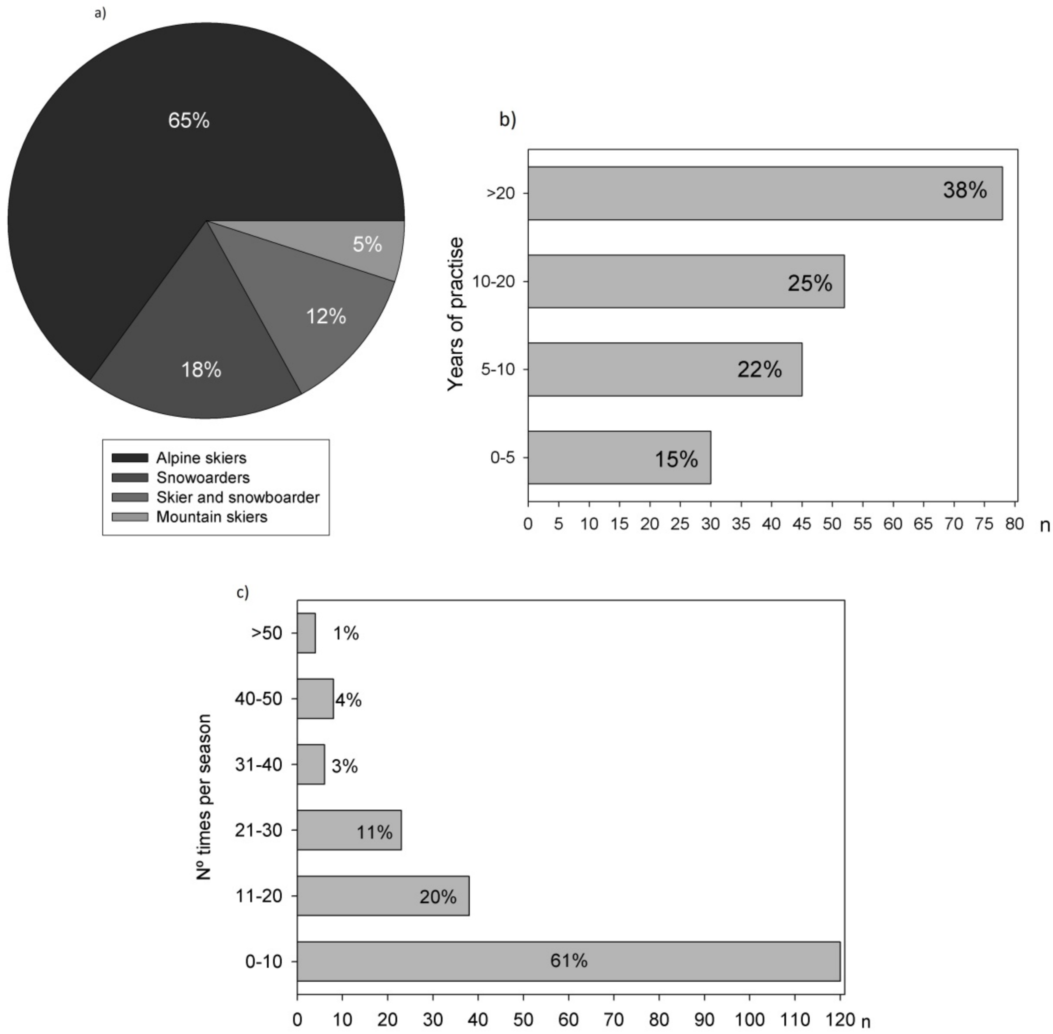

Figure 2: Sports habits: a) modality of skiing, b) Years of practice, c) Times per season
X axis number of respondents

3.4.3.3 Influence of meteorology and nivology

This section assessed the importance and actions that skiers took regarding snow and weather conditions. Skiers were asked to rate the importance they gave to the different snow and weather conditions from 1 to 5 (Question 8), with 1 being little or 5 very much. Figure 3a shows the results thereof. Skiers gave an importance of 4.3 points on average to the fact that there is rain, followed by 4.1 to windy conditions, 4.0 to the quality of snow, 3.8 to visibility, 3.7 to snow depth, 3.6 to the number of open ski lifts and 3.4 to the number of skiable kilometers. Skiers seem to be little concerned by cold conditions (2.4), preferring this to very warm (2.9), or snowfall days (3), or bad road conditions for accessing the ski area (3). These responses were analysed using ANOVA to determine different perceptions among different groups of skiers. Comparisons made between the different age groups showed significant differences for the "rain" factor. There were different opinions between the younger age group of 18–25 years in the score for the importance of rain (3.6) and the age groups of 46–55 and 56–65 (4.2). The difference of means yielded a value with F=2.87 and p-value=0.024. There was also a difference between different types of skiing for the variables of snow depth: snowboarders gave an average importance of 4.1 to the fact that there is sufficient snow, while alpine skiers gave 3.5 (F=3.09, p-value=0.036).

Mean comparisons were also made for the different groups according to practice experience, but no significant differences were found.

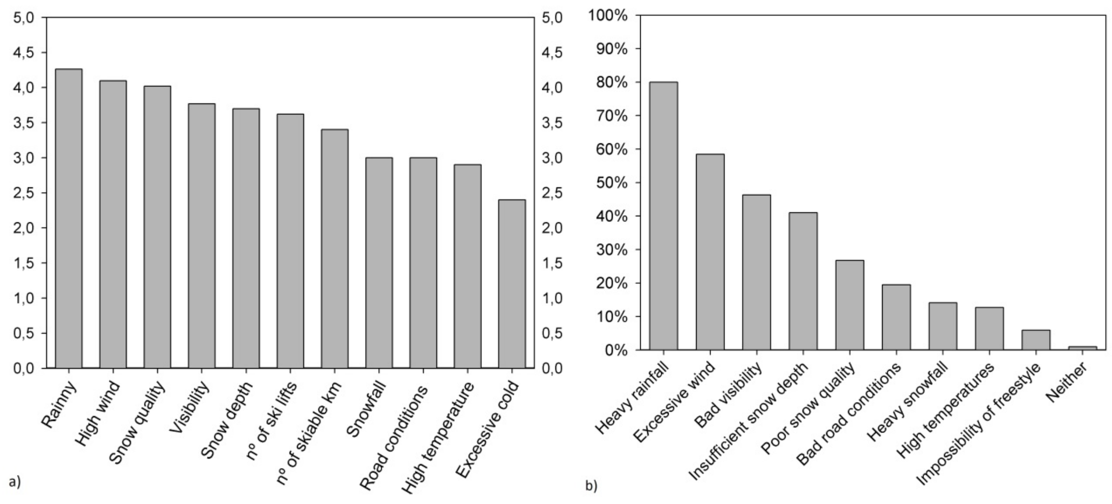

Figure 3: a) Mean values of the importance given by the respondents to different meteorological and snow conditions. b) Percentage of responses to situations that respondents would stop skiing a day that they had planned for it.

The skiers were also asked about which meteorological and snow condition would lead to them refusing to ski in a day planned for this. Figure 3b shows that 80% of skiers would not go skiing on rainy days, 58.5% would not go on a day of excessive wind, and 46% would not go under poor visibility conditions. Furthermore, 41% would not go skiing when the snow depth is very low, and of these, 10% would not ski when this is only limited to ski runs and they cannot practice freestyle skiing. Comparisons were made between the different age groups, time of practice and place of origin, and no significant differences were found.

Overall, 91% percent of respondents reported having been affected by poor snow conditions in the past in their usual place of skiing, and they were asked what they did in these situations. A total of 49% of answers indicated that they skied less often but whenever possible in the habitual place, 21% skied in the usual way despite poor snow conditions, 10% would not ski and looked for another mountain activity, 10% would travel farther to seek good snow conditions, 8% stopped skiing during the whole season and 3% responded "other" (Figure 4). Comparisons were made using ANOVA for the different age groups, degree of practice experience, number of times of practice and typology of skiing. Although no significant differences were found for any of these comparisons, skiers who practiced from 1 to 10 and 11 to 20 times per season mostly chose the option of skiing less often but whenever possible in their usual place of practice. Also, mountain skiers were more likely to continue skiing in the usual way despite bad snow conditions, while snowboarders more often chose the option of skiing less often in the usual place (F=2.60, p-value=0.060).

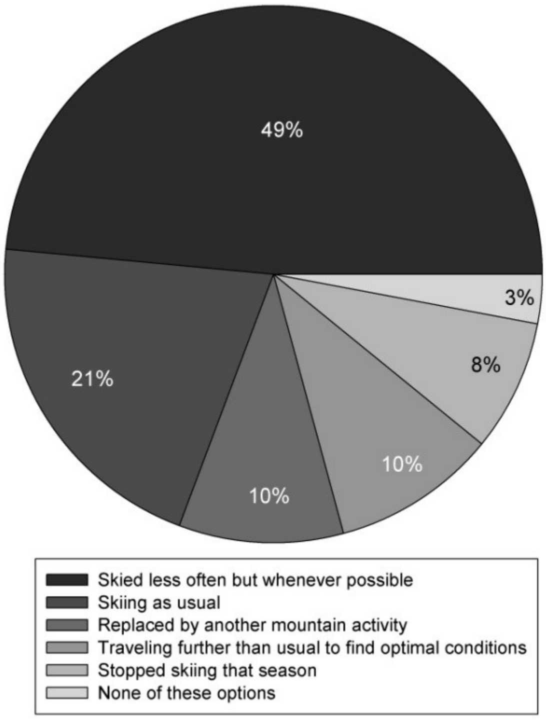

Figure 4: Adaptation of skiers to a past situation of bad snow conditions

3.4. 3.4 Perception of climate change and adaptation responses

In the fourth section of the questionnaire, skiers were questioned about their perception of climate change and how they would behave, from a skiing perspective. Figure 5 shows that 77% of respondents are almost sure or probably that climate change affects the Pyrenees, but this perception falls drastically when asked if they believe that it affects ski tourism (48%), with only 15% who were sure of that. The number of people who think that climate change will impact ski tourism in the Pyrenees in the future (without specifying any stipulated time frame) rose to 76%. Nevertheless, a large percentage of respondents (18%) were not sure about this, and 7% of them were skeptical that climate change will affect skiing.

Comparisons were made using ANOVA for the different age groups, degree of practice experience and typology of skiing for the three questions described above. Significant differences were found with regard to climate change already affecting the Pyrenees in a global way. People with short experience of skiing (0–5 years) believed that climate change affects the Pyrenees in a general way, while more experienced skiers (>20 years of practice) showed in the three questions that climate change affects the Pyrenees less or it does not affect them at all, with a great difference and a large number of respondents who say it does not affect anything, nor will it affect anything in the future. The post-hoc significance of ANOVA test showed differences between means of the two groups ($F=2.831$, $p\text{-value}=0.039$). There also exist differences between different typologies of skiing ($F=5.46$): while alpine skiers thought that climate change only affects "probably" in the Pyrenees, snowboarders ($p\text{-value}=0.004$) and mountain skiers ($p\text{-value}=0.044$) mostly thought that climate change has a substantial effect on the Pyrenees. Although the perception of climate change was not significant in terms of age, it was observed that skiers in the age groups of 18 to 45 years mostly believed that climate change affects the Pyrenees considerably, while older people mostly selected the option of only affects "probably".

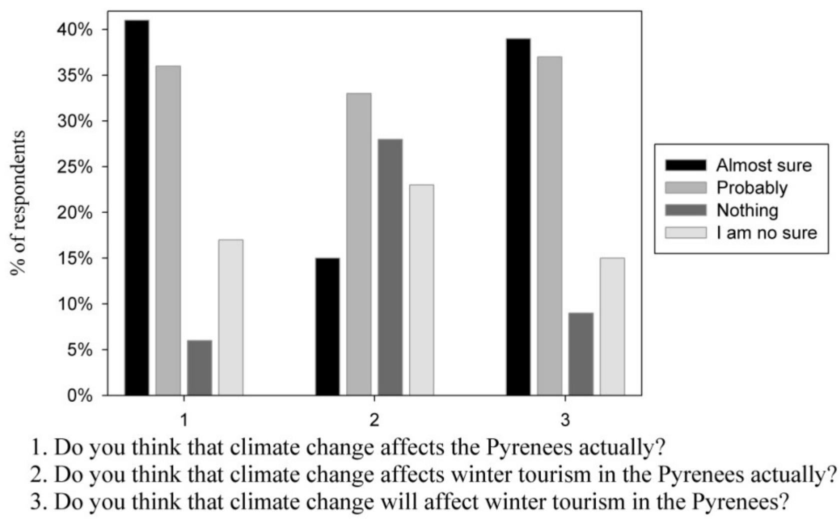

Figure 5: Perception of skiers on the condition of climate change in the Pyrenees.

Respondents who though “almost sure” o “probably” that climate change will affect skiing were questioned about what weather and nivological conditions they think will be most affected, scoring them from 1 to 5 (Q15). Temperature received an average score of 4.0 points, followed by the amount of snow (3.9), snow quality (3.6), snowfall (3.6), rainfall (3.5) and windy days (2.5).

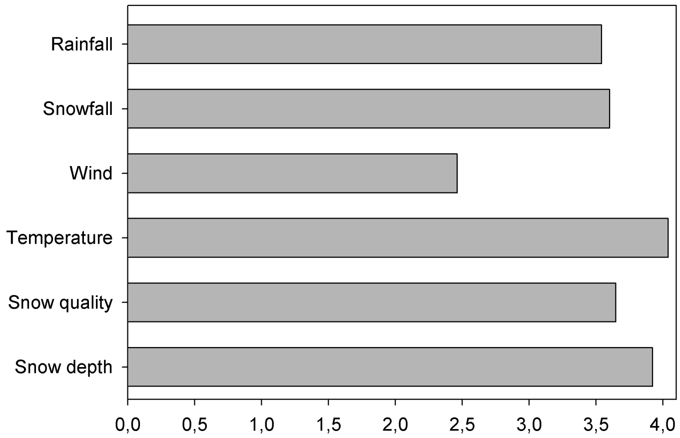

Figure 6: Scores about what weather and snow conditions will be more affected by climate change

The second part of this section explored adaptation measures adopted by the skiers for future bad snow conditions. To this end, different responses to adaptation measures were explored, such as how to replace the ski destination, the price of the pass or to shift to new activities. A total of 66% of respondents stressed their willingness to travel to farther ski destinations with better snow conditions. Only 36% of respondents would accept paying for a more expensive ski pass in order to compensate the losses of the ski industry facing shorter ski seasons and the price of the increasing snowmaking expenses. Finally, they were asked what mountain activity they would do if they could not ski. The questionnaire gave the choice of multiple answers. The responses were n=64 affirmed that they would hike, n=35 would switch to mountain cycling, n=28 alpinism, n=26 climbing, n=22 snowshoeing, n=19 trekking, n=11 canyoning, n=10 trail running and n=6 snowsled.

3.4.4 Discussion and conclusions

This study aimed to deepen the attitude of skiers regarding snow and weather conditions, and about how climate change is affecting and will affect them. For this purpose, we used a novel mixed system approach of combining online and *in-situ* collection of surveys. The surveys were designed following previous studies (referenced in the Introduction) so that the results are highly comparable with other geographic areas. Despite the survey being distributed randomly, the final structure of the respondents exhibited a clear gender imbalance (80.5% males vs. 19.5% females). This contrasts surprisingly with the studies by Vivian (2011), Dawson et al. (2013) and Rutty et al. (2015), where the majority of respondents turned out to be women. This could be explained because online surveys were provided in alpine and ski clubs in Spain, in which there is a very strong masculine composition.

The dominant age group was from 26 to 54 years (35.4 average); they were mostly experienced (or not) skiers who practice skiing frequently (average 13 days per season), but do not have (80.5%) an annual ski pass. Most studies that analyse climate change and ski tourism focus on the thickness of snow or the possibility of making artificial snow as the key element for success in a season. However, as already seen in other studies, such as Gilaberte et al. (2018), rain or wind are decisive factors for skiing attendance. In this study, respondents showed that rain, wind or poor visibility exceeds snow conditions in importance. This result coincides with Scott et al 2008, Steiger et al, 2015 and Vivian (2011), (who reported that the absence of rain, wind and good visibility were the most featured elements in skier preferences in Canada),

A total of 91% of respondents have recently suffered a year with poor snow conditions. Under such conditions, the majority (49%) continued attending the same ski destination, but reduced the number of ski days. Many respondents (21%) reported that they continued to ski as usual even though snow conditions were bad. It is unrealistic to assume that all skiers will react the same to marginal snow conditions and a changing ski sector (Dawson and Scott, 2013). Some studies make distinctions between beginner and experienced skiers. According to several studies (Cocolas, Walters and Ruhanen, 2016), expert skiers are disproportionately more likely to continue skiing despite poor snow conditions compared to beginners and occasional skiers. Other studies (Behringer et al., 2000; Dawson, Havitz and Scott (2011); König, (1998), Dawson et al, (2013) differ in the last affirmation and show that experience skiers are more sensitive to the bad snow conditions. In those works, the self-rated expert skiers indicated that they were more likely to exhibit substitution behaviour (activity, spatial and temporal) in comparison to intermediate- and beginner-level skiers – both currently and in prevision of future impacts of climate change. In Steiger et al, (2015) a highly significant negative relationship was found between skiing skills and the rating of all weather variables, meaning that beginners are more likely to not go skiing in case of unfavorable weather compared to intermediate and expert skiers. A highly significant positive relationship was found between age and weather sensitivity, meaning that older respondents are more likely not to go skiing due to the weather than younger skiers. Although our study does not explicitly refer to any question of skiing proficiency, if the response is analysed according to the number of times a respondent went skiing in a season, it may result in more experienced skiers being the most likely to stop skiing in poor snow conditions, as in these cited studies.

As for the perception of skiers about climate change, 48% of respondents thought that climate change is almost sure to be already affecting skiing in the Pyrenees, while 76% think that it will be affected in the future. We found differences in the perception of climate change between the different age groups and consequently those that take more or less time practicing the sport. The factors that the skiers think will be most affected are the temperature and the thickness of snow. The literature shows that one of the most frequent behaviours of skiers in the face of climate change is adaptive responses (Pickering et al., 2010; Scott, McBoyle and Minogue 2007). To more fully understand climate-induced behaviour change among alpine skiers, it is useful to draw upon Iso-Ahola's (1986) theory of recreation substitution. The theory of substitutability suggests that when individuals are no longer able to participate in an activity (e.g. due to poor snow conditions or the closure of local ski areas), they may substitute that activity with another (activity substitution), change the timing/intensity with which they participate (temporal substitution) or alter the location of practice (spatial substitution) (Dawson et al, 2013).

Our results also show the adaptive behaviour of skiers, both in terms of movement, frequency of activity and substitution of skiing with other mountain activities. It is also interesting to note that the majority of the skiers are not, in principle, amenable to paying for more expensive ski passes to face the likely economic impacts derived from the increased expense of snowmaking and the maintenance of ski resorts for shorter ski seasons. In this sense, the most demanded activities were hiking, mountain biking and climbing, when it is not possible to ski.

The study of the impact of climate change from the point of view of demand has been less studied; however, it is fundamental to know the behaviour of tourists and the vulnerability of the ski sector to climate change. These types of approaches can also serve as useful tools for station managers or regional planners. The results of our survey are consistent with previous studies (Behringer et al., 2000; Dawson et al., 2011, 2013; König, 1998; Pickering et al., 2010; Unbehaun et al., 2008; Vivian, 2011). We have seen that weather and climate are extremely important for skiers, and estimations based only on snow availability results are very limited (Rutty and Andrey, 2014). The different perceptions on the issue by the local population could indicate the best strategy for implementation of different adaptation and mitigation by the different stakeholders and levels of government involved. Despite more analysis being needed to apply to larger samples of respondents and other mountainous areas of Spain. Our results clearly point to the need for diversification of touristic activities around ski areas, aiming to deseasonalise the tourist demand, and to increase the flexibility of ski resorts to offer different touristic products depending on the specific climate and snow conditions.

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3.5 LOCAL SENSITIVITY OF THE SNOWPACK TO CLIMATE CHANGE IN TWO SKI RESORTS IN CENTRAL PYRENEES.

Abstract

The Pyrenees host one of the largest ski region in Europe after the Alps. In this region, winter tourism is one of the main source of income and driving force of local development. However, this activity was identified as one of the most vulnerable to future climate change. This study intended to analyze the vulnerability in two Pyrenean ski resorts: Ordino-Arcalís in Andorra and Formigal in Aragon, (Spain) to the projected changes on snowpack under different future climate scenarios. Both local and regional scales were considered. The number of days with at least 30 cm of snow depth is analyzed under two climate change scenarios (+2ºC and +4°C) with and without technical snow (grooming and snowmaking) in two orientations NW and SE for the two ski resorts. This study shows significant differences in terms of climate sensitivity due to local factors such as aspect or the effect of slopes management. The reduction in the number of days available for skiing (> 30cm thickness) is reduced in Formigal by 9%-19% and 33%-39% in NW and SE aspect respectively under a heating scenario +2°C and 40%-72% (NW) and 84%-93% (SE) aspect under a scenario +4°C. In Arcalís number of days available for skiing is reduced between 5% and 13% in (NW) and 12% -28% in SE under a heating scenario +2°C. The number of days is reduced between 13%-44% (NW) and 41%-61% (SE) under a heating scenario +4°C. In all cases taking into account the snowmaking processes. This different level of vulnerability also will lead to different needs of adaptation strategies even in the same ski resort.

KEYWORDS: Climate change, Pyrenees, Ski resorts, Snowmaking, Slope aspect.

3.5.1 Introduction

The Pyrenees host one of the largest ski region in Europe after the Alps, this activity was identified as one of the most vulnerable to a future climate change (Beniston, 2003; Scott, 2006). In the last 20 years, most of the main ski regions of the world have been assessed in terms of climate change impacts (Gilaberte et al, 2014, Steiger, 2018). However, the validity and relevance for decision makers of many studies suffers from three important limitations: the omission of ski management of slopes in the modeling process (snowmaking and grooming), the use of inappropriate snow and ski reliability thresholds and indicators and the use of inappropriate spatial and temporal scale resolutions (Steiger et al., 2018). This context turns the necessity to improve the accuracy of local modeling of snow at ski resort scale a priority to achieve more reliable and meaningful results for ski managers, in order to make relevant the impact assessment for their future planning.

One of the most used indicator for evaluated ski reliability is the "100 day rule" proposed by Witmer (1986) and frequently applied in subsequent studies (Abegg, 1996; Abegg, Agrawala, Crick and De Montfalcon, 2007; Dawson and Scott, 2010; Elsasser and Bürki, 2002; Koening and Abegg, 1997; Moen and Fredman, 2007; Pons et al., 2012; Scott et al., 2003; 2007; Steiger, 2010). This rule postulates that a ski resort has natural ski reliability if there is sufficient snow cover (at least 30 cm) for 100 days annually between December and April in 7 of every 10 years. More recently, this indicator has been questioned because the 30-cm threshold is not equally applicable to all ski resorts given their different characteristics (Pons, López-Moreno, Rosas-Casals and Jover, 2015), and because the thickness and longevity of snow cover is normally estimated for natural snow, with no account taken of the production of artificial snow.

Some studies started to include snowmaking in the snow modeling of climate change impact assessments using different periods of production, snow-base layer and thresholds (triggering temperature and snow depth). Pons et al. (2012,2015), Scott et al., (2003, 2007); Steiger (2010); Steiger & Abegg (2013); used the dry-air temperature to control the production decision (threshold of -5°C or -2°C) and Rixen et al. (2011) the dew-point temperature (threshold of -4°C). Some other studies used the -2°C threshold of wet-bulb temperature, in fact, the most relevant meteorological parameter which is used by professional snowmakers (Olefs et al., 2010; Hanzer et al., 2014; Spandre et al., 2016a).

Most of the studies used as start and end dates for snowmaking respectively the 1 November and the 30 March. Damm et al. (2014): Hanzer et al. (2014) and Spandre (2016b) divided the winter season into two periods: the "base layer" snowmaking period (1 November to the 15 December) when the model can produce as much snow as possible and the "improvement snowmaking" period (16 December to the 28 February) when a minimum snow depth is maintained (60 cm). However, professional snowmakers may differ in some cases (Hendrikx and Hreinsson, 2012; Spandre et al., 2016a). Besides the snowmaking, grooming of ski slopes is a key issue in the process of slope preparation and management. The snow density leads to differences in average temperature of the snowpack (Rixen et al. 2004) that can contribute to lengthen the ski season. Observed sites with groomed snow shown an average 1°C difference of the ground temperatures compared with ungroomed slopes, leading to soil frost in several occasions. Such, changes in the thermal behavior of the snowpack delay the melt-out date by several weeks (Rixen et al., 2004; Keller et al., 2005).

Finally, few attention have been paid to the effect of local geographical features in the sensitivity of ski resorts to future climate change. Only few studies have included geographical features when modeling snow conditions in ski resorts (Hanzer et al., 2014, Spandre, 2016a) and none has analysed the sensitivity of local geographical features beyond the elevation in future climate change impact assessments. 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 et al, 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. 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).

Here we present the modeling and the results of the snowpack sensitivity (expressed as number of days with at least 30cm of snow depth) to different climate change scenarios in two Pyrenean ski resorts (Ordino-Arcalís in Andorra and Formigal in Aragon, Spain). It captures the expected variability due to the influence of local scale geographical features of the resorts such as aspect, elevation distribution as well as the effect of technical management of the slopes (grooming and snowmaking) and the consequences of the heterogeneity of the local sensitivity to the regional scale.

3.5.2 Methods

The study area comprises two ski stations in Central Pyrenees. Arclís is located in the northernmost part of the Andorran Pyrenees. Its heights range from 1940 to 2625m, has 30km of runs and 60% of its surface is artificially ski covering. Formigal is located in Aragonese Pyrenees, is the largest of these stations, with 137 km of ski runs and a capacity of nearly 40.000 skiers/h. The elevation range at Formigal is 1500 to 2250 m.a.s.l. the snowmaking covered surface of the station is 48 kilometers.

The two ski resorts, Ordino-Arcalís in Andorra and Formigal in Aragon, (Spain), were deeply analyzed taken into account both local geographical features as well as the effect of the technical management of the runs. Principal Component Analysis was used to classify the main areas of the resort based on the geographic features (5x5m elevation, aspect and steepness grids) and identify the main representative areas with common local features. Figure 1 shows the classification of the Arcalís ski resort in the main areas with similar geographic characteristics. From this classification, different centroids values have been chosen to have an altitude, steepness and aspect value for each area.

A first area characterized by an altitude average of 1844 and 2055 m respectively for Formigal and Arcalís and a relatively steepness of 16º for both resorts (sector 1). A second area with an average altitude of 1979 and 2350 meters respectively and a slope steepness of 20º and 21º (sector 2). Finally a third area is characterized by the highest zone of the ski resort, with an average elevation of 2123 and 2500 m and a steepness of 24º and 25º for Formigal and Arcalís respectively (sector 3). Regarding aspect of slopes in both cases, Formigal and Arcalís, they can be classified mainly in North-West (NW) or South-East (SE) thus these two aspects have been applied to the 3 areas previously described. Table1 shows the values for each variable in each area of Arcalís and Formigal.

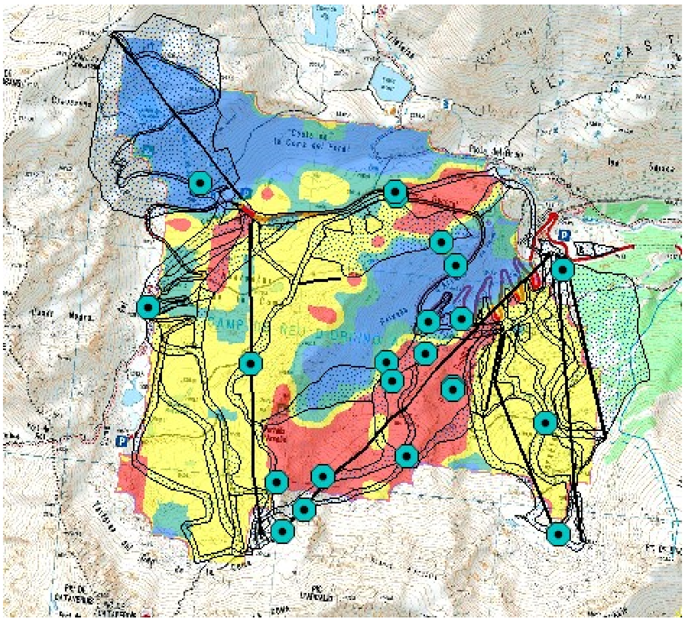

Figure 1: Classification of the Arcalís ski resort surface in different groups with similar geographic characteristics (elevation, aspect, steepness). Blue (sector 1), yellow (sector 2) and red (sector 3).

	FORMIGAL		**ARCALÍS**	
	Elevation (m)	**Steepness (degrees)**	**Elevation (m)**	**Steepness (degrees)**
Sector 1	1844	16	2055	16
Sector 2	1979	20	2350	21
Sector 3	2123	24	2500	25

Table 1: Values of altitude, steepness and aspect for each Arcalís and Formigal areas drawn from the clustering analysis and assumed as different sectors with similar topographic characteristics.

Natural snowpack evolution was simulated for each of the areas identified at each ski resort for a control period (2010-2014 for Formigal and 2012-2014 for Arcalís). After this, snow energy and mass balance was simulated in the different representative areas using the Cold Regions Hydrological Model (CRHM) (Pomeroy et al. 2007) assuming different magnitudes of climate warming (increases of 2°C and 4°C in the mean winter temperature). Values of maximum and minimum temperature, humidity, precipitation, radiation and wind of the nearest automatic meteorological station were used to feed the snow model. Snowmaking and grooming were also included in the modeling process. To include snowmaking, the hourly wet-bulb was computed and a triggering value of -2ºC. The wet-bulb temperature have been used to start producing snow from 18h to 9h from 1st November to 1st March with a maximum of 10cm per day based on the practices that professionals reported. In order to represent grooming an average density of 500 kg/m^3 was applied to the snowpack. This value was the average density observed at different ski resort points performed during the season. Only the first weeks of operation the density of the snowpack was lower with values around the 300 kg/m^3.

Finally, in order to assess future climate sensitivity, a increase of +2°C and +4°C was forced to the daily temperatures data used to feed the model. In this case only temperature changes were analyzed it has been identified that this variable would be the main driver of future change in the snowpack in the Pyrenees since precipitation changes at this region and elevations has been projected to be less significant (López-Moreno et al. 2015) and with an great interannual variability. Finally, the number of days with at least 30 cm of snow has been computed for each area of the ski resort and each scenario.

3.5.3 Results

In this section we present the results of the evolution in the number of days with at least 30cm during the control period and two climate change scenarios (2ºC and 4°C). Table 2 and 3 show the number of days with at least 30cm of snow for Formigal and Arcalís for sector of the ski resort and for each scenario based on altitude and aspect (NW and SE). The effect of grooming and snowmaking (technical snow) is also analyzed. The value of steepness is not represented because the influence of this factor in the model is not significant compared to altitude, aspect and snow management.

	NW						SE					
	NATURAL SNOW			TECHNICAL SNOW			NATURAL SNOW			TECHNICAL SNOW		
	CP	+2°	+4°	CP	+2°	+4°	CP	+2°	+4°	CP	+2°	+4°
1850 m	141	92	20	156	127	43	134	36	9	145	88	24
1980 m	150	116	32	158	135	60	149	56	13	149	97	32
2125 m	159	132	81	161	147	96	169	71	26	160	108	43

Table 2: Number of days with at least 30 cm of snow based on altitude and aspect (NW and SE) in the control period 2010-2014 (CP) and in two different climate scenario (+2°C and +4°C) and analyzing the effect of technical snow in Formigal.

	NW						SE					
	NATURAL SNOW			TECHNICAL SNOW			NATURAL SNOW			TECHNICAL SNOW		
	CP	+2°	+4°	CP	+2°	+4°	CP	+2°	+4°	CP	+2°	+4°
2055 m	226	73	51	206	180	116	137	62	10	162	116	63
2350 m	262	190	104	220	202	183	224	111	42	196	158	90
2500 m	257	221	173	228	216	199	235	168	71	212	186	126

Table 3: Number of days with at least 30 cm of snow based on altitude and aspect (NW and SE) in the control period 2012-2014 (CP) and in two different climate scenario (+2°C and +4°C) and analyzing the effect of technical snow in Arcalís.

In the control period (2010-2014), Formigal reached the 100 day rule, a minimum of 100 days with at least 30 cm of snow at all the three different elevation both with natural snow conditions and with technical snow condition (snowmaking and grooming). In a +2°C scenario SE slopes don't reach these thresholds with natural snow conditions and low elevations not even with technical snow. Mid and high elevations reach or almost reach this threshold thanks to slope preparation. In NW slopes only lowest sectors don't reach this threshold with only natural snow. In a more severe climate change scenario (+4°C), even with slope preparation, the 100-days threshold is not reached in any sector of the ski resort. Only high areas of the NW slopes are close to it thanks to slope management.

In the particular case of Arcalís, in the control period (2012-2014) the 100-days threshold is reached for all the sectors of the ski resorts both with natural snow and with snow management of slopes. In a +2°C scenario, only the lowest sectors of SE slopes don't reach the threshold with natural snow conditions but thanks to slope management the whole ski resort could be above 100 days of reliable skiability. Regarding the NW slopes only the lowest sectors don't reach the threshold with natural snow. In a +4°C scenario none of the SE sectors would reach the 100-day thresholds even the highest areas will have still high values (70 days) with only natural snow. With slope management only highest parts of the SE slopes will be above the 100 days of reliable skiability. In the NW slopes, only low elevations will not reach the threshold while the whole ski resort is still reliable (more than 100 days) under a severe climate change scenario thanks to snowmaking and slope grooming.

Figure 2 shows the percentage of change on number of days with at least 30 cm of snow in Formigal. A +2°C scenario leads to decreases between 17% and 35% considering only natural snow and decreases between 9% and 19% with technical snow in NW slopes. In SE slopes decreases are much more sever with values ranging from 56% to 73% considering only natural snow and values ranging from 33% to 39% considering slope management.

In a +4°C scenario NW slopes will suffer a decrease of 49% to 86% considering only natural snow and 40% to 72% considering snowmaking and grooming. In SE slopes, the impact is higher with values from 84% to 93% considering only natural snow and form 73% to 83% considering slope management.

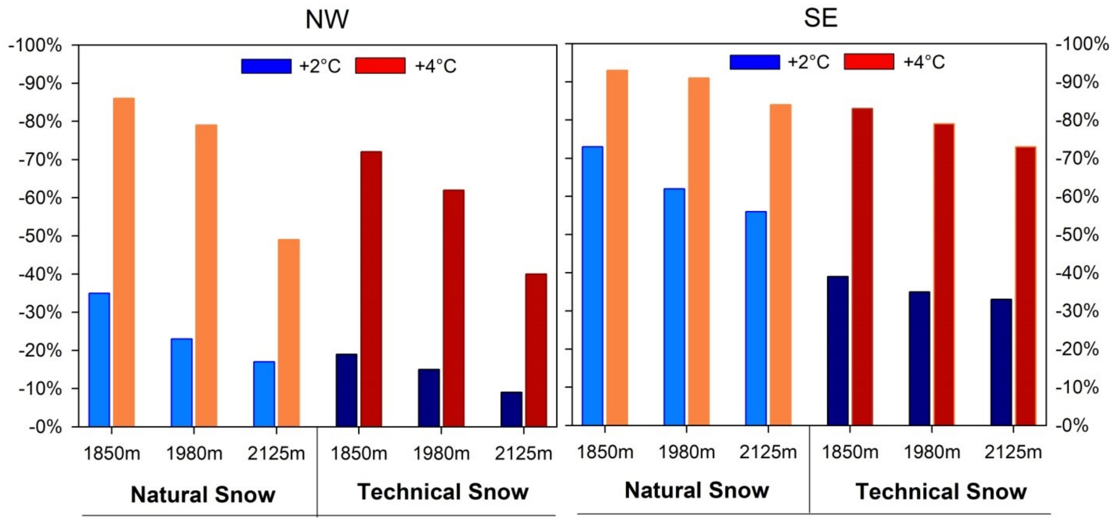

Figure 2: Percentage of change on the number of days with at least 30 cm of snow based on altitude and aspect (NW and SE) in two different climate scenario (+2°C and +4°C) and analyzing the effect of grooming and snowmaking (technical snow) in Formigal.

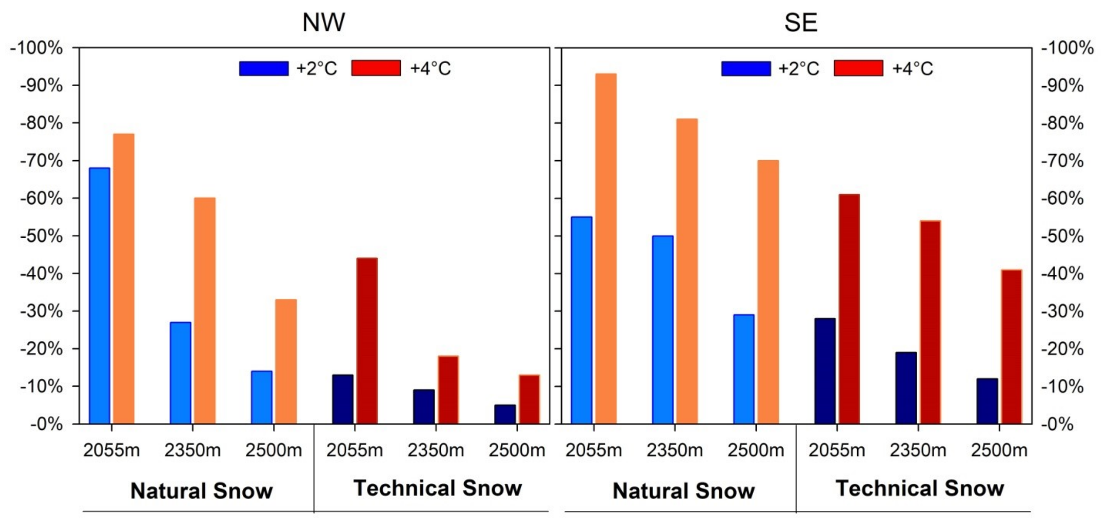

Figure 3: Percentage of change in the number of days with at least 30 cm of snow based on altitude and aspect (NW and SE) in two different climate scenario (+2°C and +4°C) and analyzing the effect of grooming and snowmaking (technical snow) in Arcalís.

In Arcalís a +2°C scenario leads to decreases between 14% and 68% considering only natural snow and decreases between 5% and 13% in NW slopes. In SE slopes decreases are much more sever with values ranging from 29% to 55% considering only natural snow and values ranging from 12% to 28% considering slope management.

In a +4°C scenario NW slopes will suffer a decrease of 33% to 77% considering only natural snow and 13% to 44% considering snowmaking and grooming. In SE slopes, the impact is higher with values from 70% to 93% considering only natural snow and form 41% to 61% considering slope management.

3.5.4 Discussion and conclusions

This study shows the differences in the sensitivity of the snowpack in different areas in the same ski resort with different geographic characteristics (altitude, steepness and aspect) as well as the effect of snowmaking and grooming under two climate change scenarios. Congruent with previous studies (López-Moreno et al, 2013), results show that the altitude and slope aspect is relevant to natural snowpack. On the other hand, snowmaking and grooming have an impact on the capacity to ensure reliable ski days along the season.

Aspect of the slopes of a sector and its altitude determine the reliable ski days as well as its sensitivity to future warming. With a temperature increase, the differences observed between the NW and SE slopes considerably increases. On the NW slopes above 2100 meters and taking into account the effects of snowmaking and grooming, the skiability in both Formigal and Arcalís can be considered reliable. At the lowest elevations with a SE orientation the number of skiable days is reduced considerably. If snowmaking was not available, an increase of 2ºC could greatly compromise skiability, especially in the slopes with a greater exposure to solar radiation. Only the 100-day threshold could be reached on the NW slopes and above the 1970 meters. Taking into account the snowmaking, the average number of ski days would be about 88 days and 126 for slopes less exposed to radiation.

A temperature increase of 4ºC, could lead to a more critical situation for the practice of skiing. Skiability at low levels would be practically impossible without the snowmaking. In slopes with favorable aspect and at higher elevations, an average close to the 100-days threshold could be reached but not for the SE slopes in the case of Formigal. In the case of Arcalís only low elevations, both in NW and SW slopes would have a critical situation with natural snow. However, thanks to snowmaking and grooming the whole ski resort would be reliable even with a sever increase of temperatures. Compared to other ski resorts in the Pyrenees; Formigal and Arcalís can be considered as low vulnerable to climate change or very resilient in the case of Arcalís. However, big differences in the level of the ski reliability inside the same ski resort have been identified. Thus different adaptation strategies can be designed and adapted for different sectors regarding the level climate sensitivity. For example, in Formigal, considering only average characteristics of the ski resort, snowmaking can be considered as a suited adaptation strategy. However, looking to the sensitivity of the different sectors considering local geographical features show that in a sever climate scenarios snowmaking does not assure skiability to all the sectors.

Thus, both ski resorts showed a very different vulnerability within the same ski resort based on the geographic features of the area. Different areas inside a same ski resort could have very different vulnerability to future climate change based on aspect, steepness or elevation. Furthermore, the technical management of ski resorts, such as snowmaking and grooming were identified to have a significant impact on the response of the snowpack in a warmer climate. 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 winter tourism industry and achieve more relevant results and indicators for the ski managers and public administrations in order to plan management and adaptation strategies.

Also be considered in future studies the adaptation of the skiability threshold based on the steepness of the slope and type of land cover. Here and in most of the studies a constant value of 30 cm is assumes as the minimum required snow-depth. However, the type of the land cover (grass, rocks, bushes, etc) and the steepness have a significant influence on the minimum snow depth. This should be studied and included in future research to achieve a more accurate assessment of the snow reliability at local scale, in different sectors of a ski resort and evaluate its sensitivity to climate change. Finally, in this study the same snowmaking capacity has been assumed for all the sectors while temperature laps rates would also affect this issue. Air and wet-bulb temperature lapse rates and their impact on snowmaking would be included in future snow modeling developments in order to include this variable to the sensitivity analysis.

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4. DISCUSIÓN GENERAL

A lo largo de esta tesis doctoral se ha investigado la influencia del tiempo atmosférico, la variabilidad climática interanual, y el cambio climático en el turismo de esquí en el Pirineo Central español y Andorra. Se trata de un estudio novedoso por su metodología y su alcance territorial. A partir de los años 90 empezaron a surgir estudios que relacionaban el cambio climático y el turismo de invierno sobre todo en la zona de los Alpes y Norteamérica. El enfoque de estos estudios no resulta sencillo en cuanto a la metodología a emplear, debido en primer lugar al propio dinamismo del sistema climático, la heterogeneidad y complejidad topográfica de las montañas. La disponibilidad de datos climáticos lo suficientemente consistentes y extensos en el tiempo es otra de las dificultades comunes en este tipos de estudios. En el primer capítulo de los resultados se realizó una revisión bibliográfica de los estudios realizados a nivel mundial sobre el tema con el fin de identificar las metodologías de trabajo y ver posibilidades de avance o mejoras. En dichos estudios se han identificado 3 metodologías principales de trabajo: Aquellas que utilizan escenarios de cambio climático de modelos generales de circulación atmosférica para explorar los posibles impactos del cambio climático en el turismo. Los escenarios de emisiones más utilizados son los publicados por el Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC). Otros estudios aplican escenarios regionales de cambio climático disponibles tras un proceso de *downscaling* (estos no están disponibles para todos los países ni para todas las regiones montañosas). Por último están aquellos estudios que utilizan el método de análisis análogo. Este último método consiste en equiparar los impactos observados en el turismo de esquí durante o una o más temporadas en las cuales la temperatura estuvo por encima de la media a otro escenario futuro en el que la temperatura pueda ser equiparable. Desde nuestro punto de vista la metodología ideal sería la de escenarios regionalizados de cambio climático (mediante *downscaling*) ya que permite una mayor resolución espacial de los datos climáticos. El método de análogos es el que más limitaciones presenta ya que normalmente solo tiene en cuenta los cambios en la temperatura y no otros elementos del clima que afectan al esquí. Además, las series de datos suelen ser relativamente cortas y se hace difícil separar claramente la respuesta del turismo al clima, o a otras posibles causas (p.e. situación socioeconómica durante un periodo de nieve abundante o escasa, cambios en la demanda turística, etc).

En los estudios revisados en el apartado 1 de los resultados se repiten algunos elementos considerados claves para el éxito de una temporada de esquí, como son: alcanzar unos espesores mínimos de la capa de nieve, una duración mínima de la temporada de esquí, y en algunos casos la posibilidad de fabricación de nieve artificial (este último aspecto más desarrollado en las investigaciones más recientes). Es un hecho claro que el elemento nieve es condición *sine qua non* para la práctica del deporte de esquí; sin embargo los sistemas más modernos de fabricación de nieve artificial permiten producirla a cotas más altas dónde la temperatura es más baja, y después redistribuirlas a través de la estación (Fauve, Rhyner, and Schneebeli, 2002). La técnica para fabricar nieve o conseguir que esta perdure en superficie evoluciona rápidamente. Algunas de las últimas medidas de adaptación utilizadas por las pistas de esquí en Suiza consisten en cubrir con lonas de poliuretano pistas y glaciares para protegerlas de la exposición solar. También se investiga la posibilidad de incorporar minerales al binomio agua/aire de la actual fabricación de nieve o el inyectar agua en las capas de nieve para modificar su composición física. Sin embargo, alguna de estas prácticas está siendo cuestionada por su efecto adverso en la vegetación y la calidad del agua de fusión, estando prohibidas en algunos países. En todo caso la implementación de los sistemas de nieve artificial es costoso ambiental y económicamente y muchas estaciones son altamente o completamente dependientes de estos sistemas (Clarimont 2008; François et al, 2014; Moreno, 2005).

La diferencia en las metodologías de los trabajos revisados no solo se reduce a los diferentes escenarios de cambio climático sino también a diferentes horizontes temporales, diferentes extensiones geográficas y latitudinales. Por todo ello resultó algo dificultoso poder hacer un estudio comparativo de todos ellos, pudiendo comparar directamente solo algunos de ellos. De esta manera, el primer capítulo de los resultados permite dibujar una perspectiva global de como el cambio climático puede afectar al turismo de esquí en diferentes montañas del mundo, teniendo en muchos casos precedentes de malas temporadas en las cuales el negocio del esquí se vio perjudicado. De estos estudios se desprende la general preocupación por la duración de la temporada de nieve, inviernos demasiado templados, la elevación de la cota de la isoterma 0°C y la inversión en infraestructura para la fabricación de nieve artificial. Otras de las conclusiones extraídas de esta revisión es la escasez de estudios referidos a la montaña mediterránea y en concreto para los Pirineos.

A pesar de que las montañas mediterráneas son por su latitud aún más vulnerables al cambio climático y a la variabilidad interanual que otros ecosistemas montañosos del mundo, solo 2 estudios (que relacionaran directamente el turismo de esquí y el cambio climático) se encontraban publicados en el momento de la revisión; Pons et al., 2012 y Estudio sobre el sector de la nieve en Aragón, 2009. Posteriormente se añade los estudios Pons et al., 2015 citado en varios capítulos de la tesis.

Teniendo como punto de partida los estudios precedentes citados en el capítulo 1 de los resultados, se plantea para el apartado 2 de los resultados, el análisis de las tendencias durante la segunda mitad del siglo XX de las diferentes condiciones climáticas y nivológicas que afectan al esquí, situando esta vez el área de estudio en el Pirineo Central. En este sentido se plantea la necesidad de evaluar no solo los espesores de nieve o la duración de la temporada sino muchas otras variables que se ha demostrado que afectan al esquí. Shumude, (2013) indica como no es suficiente la aplicación de la regla de los 100 días (Witmer, 1986) para valorar la viabilidad del esquí debido a la uni-direccionalidad de la medida. Otras variables climáticas como la sensación térmica (Wind-Chill[7]) (Roshan, Mirkatouli, Shakoor, & Mohammad-Nejad, 2010), el viento (Demiroglu, Turp, Ozturk, & Kurnaz, 2016), las precipitaciones (Gössling, Abegg, & Steiger, 2016; Steiger et al, 2016) son necesarias para avanzar en el conocimiento de cómo el tiempo y el clima pueden afectar al esquí tanto desde el punto de vista de la oferta como la demanda. En comparación con el número de estudios que relacionan la abundancia de nieve y la duración de la capa de nieve, casi ningún estudio ha considerado los impactos de estas otras variables climáticas que pueden ser de gran importancia para el éxito o el fracaso de una temporada de esquí y por

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Aunque este índice no tiene en cuenta factores ambientales como la humedad relativa y la radiación solar, los investigadores y la realización de investigaciones sobre este índice creen que utilizando este índice es suficiente para proteger la salud en tiempo frío. Las organizaciones meteorológicas de muchos países presentan el wind-chill a través de medios públicos y sitios de Internet.

ello este segundo capítulo de los resultados propone un análisis exploratorio retrospectivo de todos estos parámetros. Ejemplos de cómo la disponibilidad de nieve no ha sido la única cuestión determinante para el esquí lo encontramos recientemente en los Pirineos españoles. Durante el Período de Navidad en 2013-2014, y 2016-2017 las condiciones meteorológicas anticiclónicas atrajeron a un gran número de esquiadores a pesar de las malas condiciones de nieve, que causó el cierre de muchas de las pistas de esquí.

Fotografía 2: Formigal, 2/01/2017 (temporada 2016-2017). Fuente: propia

Para la evaluación de las tendencias en las distintas variables que afectan al esquí, el segundo capítulo de los resultados hace un análisis retrospectivo de la evolución desde el año 1960 hasta 2006 de aquellos elementos nivo-climático que afectan a la práctica del esquí en el Pirineo Central español y Andorra. Además, se investigó si existe una asociación temporal para las variables climáticas y nivológicas analizadas, de manera que la ocurrencia en un determinado año de buenas (o malas) condiciones climáticas o de nieve se refleje de manera similar por los otros parámetros. Para realizar los cálculos de las variables climáticas y nivológicas se utilizó datos procedentes del modelo de reanálisis MM5. Hubiera sido completamente deseable utilizar datos históricos medidos de espesores de nieve, y demás variables climáticas, sin embargo no se encontraron disponibles series temporales lo suficientemente largas, y a escala horaria para un territorio tan amplio como todo el Pirineo Central español y Andorra que permitieran hacer los cálculos pertinentes.

Uno de los aspectos más novedosos de este capítulo es el análisis de asociación entre variables climáticas, es decir el conocer para un año si la frecuencia de una variable dada de nieve o clima en un determinado año se asoció positiva o negativamente con otras variables climáticas. Nuestro análisis mostró que hubo asociaciones entre las variables. La correlación positiva entre los años ricos en acumulación de nieve con la frecuencia de días ventosos (Pearson's $r > 0.6$) y las buenas condiciones para la fabricación de nieve fue particularmente importante. En general, los años más ventosos también son los más fríos. Y estas temporadas que tienen grandes períodos de frío muestran frecuencias más bajas de nevadas intensas e intensas lluvias (-0.2).

Otro aspecto novedoso del estudio es el análisis en las tendencias en la velocidad del viento. Esta variables es muy importante y determina en gran medida las condiciones esquiables en la mayoría de estaciones. Es la razón principal para el cierre de los remontes, y en algunos días impide la apertura del complejo completo. Nuestros resultados mostraron una disminución general del (19-25%) en el número de días por temporada que superó el percentil 80 de velocidad de viento (40-45km/h) en casi todas las estaciones. En este sentido, muchos estudios en todo el mundo han informado de una disminución de la velocidad del viento en la superficie de la tierra (llamada "global stilling", resumida por Roderick, Rotstayn, Farquhar y Hobbins, 2007). Para el período 1960-2006, McVicar et al. (2010) señaló que este proceso de ralentización es mayor en elevaciones más altas. Para la península ibérica, Azorin-Molina et al. (2014) encontró que ha habido una tendencia de disminución de la velocidad del viento en invierno y primavera (coincidiendo con la temporada de esquí). Esta tendencia puede resultar positiva para las estaciones de esquí, ya que como se analizará más adelante el viento es uno de los principales motivos de cierre de las estaciones de esquí y es la 2º causa más señalada por el esquiadores como la condición que más rechazan para ir a esquiar solo por detrás de la lluvia intensa. Además, altos valores de velocidad del viento pueden ser perjudiciales para la conservación de la nieve en superficie (Dadic, Mott, Lehning and Burlando, 2010; Sprandre, 2016; Wang and Huang, 2017). Es por tanto una variables altamente condicionante en el esquí y para lo que se conoce como el “optimal ski day” (Schmude, 2013; Berghammer and Schmude, 2014).

Hasta el momento el único estudio que se ha encontrado que relaciona directamente escenarios de viento con el turismo de esquí es Demiroglu et al, (2016) que coincidiendo con los hallazgos de nuestro estudio pronostica de un 29 a 50% menos de días de cierre por fuerte viento en las estaciones de esquí de Turquía. Sin embargo el último informe del IPCC no aporta escenarios concretos en cuanto a posibles modificaciones de velocidad del viento.

Algunas de las tendencias detectadas en este segundo capítulo de los resultados deben interpretarse parcialmente en el contexto de variabilidad decadal del clima, y la variabilidad interanual, lo que hace que los resultados sean, dependiendo del período de estudio seleccionado, influenciados por los patrones atmosféricos principales (por ejemplo, el Atlántico Norte Oscilación; NAO) (Jerez and Trigo, 2013; Muñoz-Diaz and Rodrigo, 2003; Vicente-Serrano and Trigo, 2011).

En el estudio se observa un aumento de las nevadas intensas en las estaciones más occidentales del Pirineo. Por un lado puede ser beneficioso el hecho de que haya varias nevadas copiosas durante la temporada. Sin embargo, si posteriormente se acompaña de precipitación líquida o temperaturas altas en vez de otras nevadas espaciadas durante la temporada, la capa de nieve puede no permanecer el tiempo deseable y la calidad de la misma descender (Beniston and Stofell, 2016). Además, estudios recientes como Morán-Tejeda et al., (2017) destacan la disminución durante el invierno del número de días fríos y húmedos en el Pirineo que son los considerados como más favorables para las nevadas, mientras que los días secos y fríos son los idóneos para la conservación de la nieve una vez que esta está en superficie. Es por esto de la importancia de varias y sucesivas nevadas tempranas para un buen comienzo de la temporada de esquí (Falk, 2015), que garanticen el éxito en las primeras semanas de apertura e incluso durante las vacaciones navideñas. En este mismo estudio (Falk, 2015) -y en otros de los citados en el capítulo 2 de los resultados-se indica que es previsible la tendencia a la menor acumulación de nieve en las cotas bajas de las estaciones de esquí.

Como indicador final de este capítulo así como de la bibliografía que se presenta en la discusión, se observan unas tendencias claras en las series con descensos en el número de días >30 y 100cm de espesor, retraso en la apertura y duración de la temporada, descensos en los días con sensación térmica <-20ºC entre otros parámetros que se sobre-imponen a la variabilidad interanual y que se ven corroboradas con los resultados más recientes obtenidos en otras montañas europeas como en los Alpes (Klein et al, 2016).

Una posible mejora o ampliación de este estudio para posteriores investigaciones sería poder disponer de simulaciones climáticas hasta el presente y poder actualizar el análisis de tendencia realizado incluyendo los últimos años, que han sido muy variables desde un punto de vista climático y nivológico (Buisan et al., 2015).

Con el objetivo de analizar el impacto real del tiempo atmosférico en la afluencia de los esquiadores a las pistas, el tercer capítulo de los resultados ha abordado un análisis de la afluencia diaria de esquiadores a 3 estaciones de esquí del Pirineo aragonés. Este capítulo pretende conocer las preferencias del turista *in situ* y a tiempo real. En este caso se debe tener presente que la percepción y las valoraciones climáticas son individuales y en ocasión altamente subjetivas (Göslling et al, 2016). Este capítulo también relaciona la afluencia de esquiadores con el porcentaje de pistas abiertas.

La cuestión de cómo el tiempo atmosférico afecta al confort de las personas es un campo de análisis muy extenso, que no se aborda como tal en esta tesis. Los estudios más recientes tratan de parametrizar este confort aplicando índices, de manera que los resultados puedan ser comparables entre diferentes estudios. Uno de los índices más utilizados a este respecto es el *tourism climate index* desarrollado por Mieczkowski, (1985), que fué aplicado para el turismo de invierno por Amelung et al. (2014). El TCI fue diseñado para integrar las principales variables climáticas relevantes para el turismo en un solo índice numérico. Proporciona una medida compuesta capaz de facilitar una interpretación holística del clima de destino, que se puede usar para comparar destinos objetivamente. Posteriormente este índice se ha detectado insuficiente y ha sido complementado por el *Holiday Climate Index* (Scott et al, 2016). La principal mejora del HCI frente al TCI es la mayor resolución de las variables climáticas a nivel diario y la adaptación del índice a diferentes tipos de turismo. Sin embargo en base a los parámetros que incorpora no es aplicable al turismo de esquí sino es introduciendo modificaciones ya que el turismo de nieve tiene varios factores limitantes que pueden anular completamente el índice, como días de cierre por vientos extremos, nevadas intensas que provoquen avalanchas, etc. Una de las posibles vías de ampliación de este tipo de estudios para la montaña mediterránea sería la implementación de *modelos de demanda turística.* Uno de los estudios más recientes con esta metodología analiza el impacto en la demanda turística de invierno con los inputs de series temporales de espesores de nieve, nº de noches de reservas turísticas y renta *per capita* (Damm et al, 2016).

En nuestro estudio, al analizar un periodo relativamente corto de tiempo (11 temporadas de esquí) no se pretende establecer unas tendencias en la afluencia anual de esquiadores sino más bien mostrar las fluctuaciones interanuales de esquiadores muy vinculadas a la variabilidad climática interanual y a la variabilidad meteorológica. Esta variabilidad climática depende en gran medida como se ha dicho anteriormente, de los flujos dominantes durante el invierno en la península como la NAO, (Wang, Ting and Kushner, 2017). Además en estos análisis de afluencia no se aísla el factor meteorológico de otros factores como pueden ser el económico (renta *per cápita*), el precio del forfait o los costes del transporte que son uno de los más influyentes a la hora de ir a esquiar (Gilbert y Hudson, 2000; Holmgren and McCracken, 2013) junto con el calendario vacacional que sí es analizado en detalle. Hubiera sido completamente deseable el disponer de datos de afluencia diarios a pistas desde un periodo de tiempo más temprano, sin embargo la sistematización en la recogida de datos por parte de las estaciones, no se ha realizado de forma homogénea hasta la última década.

Este tercer apartado de los resultados expuesto se complementa con el siguiente que utiliza la metodología de encuestas para explorar el comportamiento del turista ante las diferentes condiciones climáticas y meteorológicas. Además, explora las posibles adaptaciones frente a situaciones de cambio climático. Hasta dónde se tiene conocimiento, este estudio es el primero que aborda esta cuestión en el Pirineo con la metodología de encuestas. Este capítulo confirma los resultados del anterior, indicando que la lluvia y los vientos fuertes son los 2 elementos que producen más rechazo a la hora de ir a esquiar seguido de la mala visibilidad que puede afectar a la seguridad. En este sentido no se corrobora completamente la hipótesis y los hallazgos de los primeros estudios revisados dónde se indica que el espesor de nieve es prácticamente la única condición indispensable para la viabilidad de las estaciones de esquí. Además un porcentaje representativo de la muestra no cree que el cambio climático esté afectando al turismo de esquí en el presente, aunque esta creencia cambia cuando las afecciones se proyectan en un futuro indeterminado.

Tras realizar un análisis retrospectivo, y un análisis de la situación presente, el 5º y último capítulo de los resultados proyecta los posibles impactos del cambio climático en el esquí en el futuro bajo dos escenario de calentamiento (+2ºC y +4ºC). Un elemento a destacar de este estudio es la incorporación de un análisis a pequeña escala (área esquiable) en el análisis, así como la incorporación en el modelado de los datos de la praxis de la gestión de la nieve artificial (calendario de producción, umbrales para su vuelco, densidad de la misma). Este punto es novedoso y no existe mucha literatura al respecto orientada hacia el turismo de esquí. Otro aspecto destacado de este capítulo es el análisis topográfico incorporando datos de elevación, pendiente y orientación que se ha mostrado altamente condicionante en la duración de la temporada de esquí. De todo ello se extrae la importancia de combinar análisis a nivel regional con otros a escala local.

Frente a los impactos que la variabilidad climática interanual, la variabilidad meteorológica y el cambio climático presentan actualmente en el turismo de esquí (y que se pronostica será mayor en un futuro) resulta imprescindible tomar medias de adaptación. A continuación se exploran brevemente las medidas de adaptación más empleadas en las diferentes montañas con industria del esquí en el mundo y se realiza una modesta aportación propia en base a los resultados y la experiencia obtenida a lo largo de esta tesis.

La medida de adaptación más extendida de todas es la fabricación de nieve artificial que se lleva a cabo actualmente en todas las montañas con estaciones de esquí (Fauve, et al, 2002; Spandre, 2016). La tecnología de producción de nieve nació en Estados Unidos, en los años 1950 y llegó a Francia en los años 1960 para innivar unas pistas de reducido tamaño y de baja altitud en los Vosgos y en los Alpes (Chamonix) (Clarimont, 2008). Su desarrollo generalizado se dio en los años 80 y ha ido extendiéndose su uso ampliamente hasta la actualidad. Actualmente ya no se usa para paliar situaciones de especial carestía sino de forma sistemática (Paccard, 2011). Actualmente Italia y Austria tienen la mayor proporción de pistas de esquí equipadas con nieve artificial en los Alpes (75% y 66% respectivamente), Francia (20%) y el sur de Alemania (17%) tienen la cuota más baja. En las regiones donde la difusión de nieve se ha desarrollado más, el objetivo de las empresas de esquí es una cobertura de fabricación de nieve del 90-100% de todo su dominio. Esto significa una mayor intensificación de la fabricación de nieve y, por lo tanto, se puede esperar un aumento de la demanda de agua y el consumo de energía para la próxima década, intensificada además por el cambio climático (Steiger, 2011). Vanham et al (2009) analiza críticamente este aumento en la demanda de agua para la fabricación de nieve indicando que muchas veces las estaciones de esquí en lugar de adaptarse a las condiciones hidrológicas prevalecientes y economizar agua durante las sequías, inducen a un círculo vicioso de extracción de agua para el llenado de los embalses o el suministro directo de cañones de nieve de arroyos y lagos. Un ejemplo de ello es el lago Davos, en Suiza que ha experimentado problemas con 28 m de bajada de nivel de agua en invierno para fabricación de nieve artificial. También en los últimos años se han registrado bombeos ilegales de agua en Austria y Suiza debido a que las cantidades de agua autorizadas eran insuficientes para las necesidades de fabricación de nieve debido a la extensión del área de esquí o la carestía de nieve natural (de Jong, 2014).

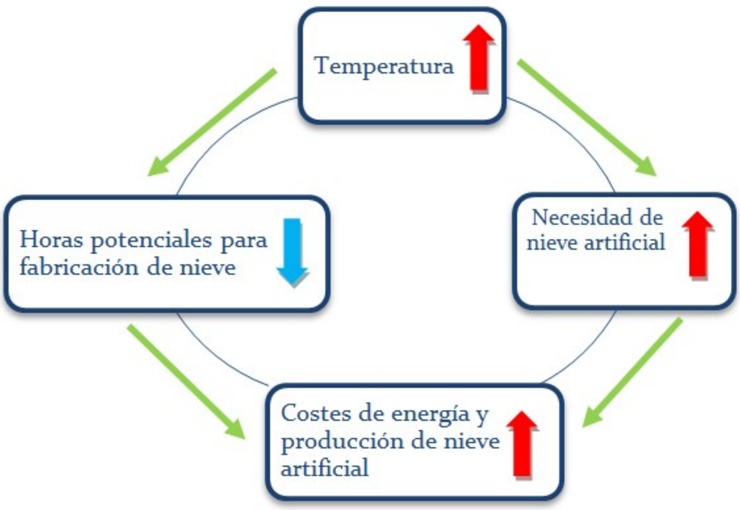

Figura 8: Ciclo de necesidad de nieve artificial. Fuente: propia.

Tal y como muestran los hallazgos del capítulo 5 de los resultados, aún con el empleo de nieve artificial algunas estaciones y muchos sectores, sobre todo los de cota más baja y los orientados en laderas sur, sur-este presentarán grandes dificultades para mantener una cantidad y espesor suficiente de nieve a principios de temporada especialmente. La estación de Formigal no se mostraba viable en el análisis bajo un escenario de calentamiento +4ºC, teniendo en cuenta además que el análisis no está modelado para la cota más baja de la estación (1700m) sino 200 metros más elevados (primer sector) y mayores elevaciones (sectores 2 y 3).

En cuanto al uso de la producción de nieve artificial, sería conveniente una profundización en el conocimiento y en la concienciación del uso energético y de agua que supone el cubrir las pistas de esquí, especialmente en los años de gran sequía, de manera que como se ha dicho, la oferta se intente ajustar en la medida de lo posible a las condiciones ambientales adecuadas con una mayor flexibilidad del negocio.

Como hemos visto el índice NAO entre otros tiene gran influencia en la variabilidad climática interanual y afecta a la acumulación de nieve. Poder prever el índice NAO con antelación sería una herramienta muy valiosa para la planificación de una temporada de esquí eficiente y de consumo energético racional de manera global. En este sentido se han realizado grandes avances en la previsión del índice NAO, (Wang et al, 2017). Dunstone et al, 2016 han desarrollado un innovador modelo climático que permite la previsión del índice NAO hasta con 1 año de antelación, si bien es verdad que actualmente estos modelos no tienen la resolución espacial suficiente para garantizar previsiones a nivel de valle, localidad o área esquiable. Un mejor conocimiento del tiempo y el clima a escala muy local ayudaría a una mejor gestión de las estaciones. Conocer las inversiones térmicas puede ayudar también a planificar la eficiencia de la nieve artificial. Por ejemplo, los cañones de Panticosa situados en cota 1000 metros son solo sostenibles por la existencia de potentes inversiones térmicas y la adaptación de los cañones para producir mucha cantidad de nieve en pocos días de condiciones favorables.

Otra de las medidas de adaptación adoptadas (aunque en mucha menor medida que la fabricación de nieve artificial) consiste en el desplazamiento de los remontes a una cota más elevada, de modo que pueda garantizarse durante más días la nieve en superficie y la fabricación de la misma. En muchas de las montañas esta medida de adaptación no es posible llevarla a cabo debido al gran impacto ambiental que supone, las dificultades logísticas y en muchos casos por encontrarse próximos a espacio protegidos.

La mayor parte de los estudios coinciden que diversificar las operaciones del complejo (múltiples actividades de invierno y operaciones de cuatro estaciones) es una de las medidas más fiables y viables que pueden llevarse a cabo. De esta manera se pretende que la "estación de esquí" se convierta paulatinamente en "estación de montaña". Dentro de los planes de "desestacionalización" de la oferta se llevan a cabo actividades de excursionismo, BTT o descenso en patines adaptados al terreno, por dentro de las estaciones de esquí.

Desde el punto de vista económico o empresarial formar parte de un consorcio más grande o de un conglomerado de esquí diversificado a nivel regional, es desde luego una de las medidas de adaptación más empleadas y aceptadas por los diferentes grupos del esquí (Scott, McBoyle and Minogue, 2007). Una de las estrategias de adaptación llevadas a cabo en el Pirineo ha sido la unión progresiva en la montaña aragonesa y andorrana de las diferentes estaciones de esquí en dominios más extensos de manera que se aúne la gestión empresarial y los pases de cara al esquiador. El último paso ha sido la creación para la temporada 2017-2018 del forfait llamado "ski Pirineos" que integra a todas las estaciones del Pirineo aragonés excepto a Astún.

La montaña mediterránea tiene sus particularidades respecto a otras zonas montañosas de Europa y sus medidas de adaptación al cambio climático deben de adaptarse a sus propias condiciones. El estudio antes citado de Morán-Tejeda et al, 2017 indica de la que durante la primavera prevalecen los días fríos y secos que permiten una mayor permanencia de la cubierta de nieve, de la misma manera López-moreno, et al (2009) señalan los meses de marzo y abril como los que mayores espesores presentan. Resulta altamente tentador abrir las estaciones de esquí durante el puente de diciembre, antes incluso de empezar la estación de invierno. Sin embargo como hemos visto las primeras semanas de diciembre no garantizan casi ningún año una apertura con éxito y el empleo de nieve artificial cubre prácticamente del 100% en algunas pistas en cota baja. Este hecho no se da únicamente en la montaña mediterránea, por ejemplo Dannevig et al, 2017 indican para Finlandia que algunos centros de esquí acortaron su final temporada no necesariamente por falta de nieve (porque que abril y mayo se presenta muchas veces más estables en cuanto a condiciones nivológicas) sino porque que carecen de la base de clientes necesarios y que sin embargo en diciembre es cada vez más difícil en términos de condiciones de nieve.

Los consorcios del esquí planifican la temporada indicando los días de comienzo y cierre antes de conocer la disponibilidad de nieve para esa temporada (de Jong 2014). Desde nuestro punto de vista quizá se debería adaptar la oferta a las condiciones predominantes de nieve y fomentar el esquí no solo al comienzo de la temporada sino también al final dónde muchas veces las estaciones cierran con buenos espesores de nieve. Realizar ofertas atractivas o fomentar la afluencia de grupos como "la semana blanca" durante los meses de marzo y en algunos casos abril puede ayudar a espaciar la afluencia durante el resto de la temporada. Actualmente esta actividad escolar de "la semana blanca" esta se lleva a cabo en muchos casos en enero, cuándo hemos visto que es uno de los meses con más saturación y concentración de la demanda de esquiadores (Gilaberte et al, 2017). En este sentido la estación de esquí aragonesa de Cerler durante la última temporada ha realizado una campaña para cambiar la "cultura" de no esquiar en primavera, si bien es verdad que recomiendan elegir el sector adecuado en función del momento del día para evitar en la medida de lo posible el exceso de "nieve primavera". En estas situaciones el precio del forfait también debería adaptarse a las condiciones reales que la estación ofrece.

Malesevka, Haugom and Lien, (2017) exploran para diversos escenarios de Noruega la posibilidad de realizar ofertas de forfait con precios más dinámicos en función no solo de la disponibilidad de la nieve sino del tiempo atmosférico de cada día, de manera que un día con condiciones meteorológicas adversas pueda resultar atrayente por una rebaja sustancial de los precios. De la misma manera proponen una reducción de los precios del forfait al comienzo y final de la temporada cuando las condiciones de nieve son pobres. Recientemente, en enero de 2017, las estaciones de esquí Pizol y Valais en Suiza han anunciado que son los primeros en Europa en ofrecer forfait de un día con descuento si el tiempo es malo. Una política de precios más dinámicos sería desde luego una medida de adaptación válida para el Pirineo cuando no todo el dominio está abierto, porque tal y como se ha visto en el capítulo 3 de los resultados la afluencia a las estaciones es 3 veces menor cuando solo un 25% del dominio está funcionado frente a cuando un 75% del mismo está activo. Así mismo, varias estaciones del Pirineo francés han propuesto rebajas en los precios del forfait en las primeras semanas de apertura dónde el rendimiento y porcentaje de apertura de la estación es bajo. Sin embargo en Andorra (Ordino-Arcalís) proponen para esta misma temporada como novedad la posibilidad de comprar un seguro meteorológico llamado "garantía meteorológica" de manera que pagando un suplemento en el forfait este puede cambiarse libremente para otro día si la situación meteorológica o nivológica (en cuánto apertura de determinados remontes) no satisface lo previsto. Esto supone en cualquier caso un incremento en el precio del forfait para el consumidor.

Finalmente, un análisis crítico sobre el medio natural, el clima y el producto de consumo –el esquí en este caso- así como la educación ambiental acerca de los impactos del cambio climático puede resultar una medida de adaptación eficaz para la montaña Pirenaica. Además, el uso racional de los recursos es imprescindible para el desarrollo de cualquier actividad en el medio natural y en la montaña en particular.

5. CONCLUSIONES GENERALES

A continuación se presentan las conclusiones principales de esta tesis organizadas en función de los objetivos planteados en el capítulo 2 (hipótesis y objetivos):

Objetivo 1:

Revisar el estado del arte a nivel mundial en estudios sobre el cambio climático en el turismo de invierno: Identificación de metodologías de estudio, lagunas y principales líneas de investigación.

Conclusiones:

1. Los primeros estudios sobre la cuestión surgen a partir de los años 90. Por zonas geográficas, Europa y Norte América son las más estudiadas, mientras que en Sudamérica y África no se han encontrado todavía estudios que relacionen directamente el cambio climático y el turismo de esquí.

2. Resulta complicado realizar una comparación entre los estudios existentes debido a las diferentes metodologías empleadas, los diferentes umbrales temporales de cambio climático y las particularidades geográficas de cada región montañosa. Los estudios coinciden en un empeoramiento de las condiciones nivológicas que permiten la práctica de los deportes de nieve.

3. Los estudios revisados basan –en su mayoría- la viabilidad del esquí en función de pocos parámetros como son los espesores de nieve, la duración de la temporada y en algunos casos la posibilidad de fabricación de nieve artificial. Muy pocos lo hacen en función de condiciones meteorológicas que afectan el confort del esquiador.

4. Los estudios revisados muestran incertidumbre acerca de cómo la precipitación podrá evolucionar y afectar al turismo de esquí.

5. En la mayoría de los estudios se indica que el hecho de haber menos nieve disponible no implica el fin del negocio del esquí, pero que sin embargo las cotas más bajas de las estaciones muestran poca viabilidad.

6. Actividades complementarias a la nieve que permitan reducir la estacionalidad en la afluencia turística serán clave para la viabilidad futura de los complejos de esquí.

Objetivo 2:

Evaluación de las tendencias en la viabilidad de las condiciones para el de esquí en el Pirineo Central español y Andorra para la segunda mitad del siglo XX.

Conclusiones:

1. El modelo de mesoescala MM5 utilizado para disponer de series temporales extensas se ajusta bien en las validaciones realizadas y por lo tanto es una herramienta útil para este tipo de estudios.

2. El número de días con una capa de nieve superior a 30 y 100 cm disminuyó en todas las estaciones de esquí durante el período de estudio (1960-2006), tanto en las elevaciones bajas como medias.

3. En condiciones de nieve natural, el inicio de la temporada de esquí se ha retrasado en cotas bajas (5-55 días) y en cotas medias (5-30 días) de media.

4. Los resultados mostraron que el número de horas potenciales para fabricación de nieve disminuyó de media entre un 8% y un 20% en cotas medias y bajas, respectivamente.

5. Se observa una disminución general (19-25%) en el número de días por temporada que superaron el percentil 80 de velocidad de viento.

6. Aquellas estaciones de esquí situadas en cotas más altas y más próximas a los frentes húmedos del Cantábrico muestran tendencias menos acusadas en la reducción de los espesores de nieve, mientras aquellas más continentales y de cota más baja presentan las tendencias más acusadas.

7. Existen asociaciones entre distintas variables nivo-climáticas. Se encontró correlación positiva entre los años con mayores espesores de nieve y la frecuencia de días ventosos, así como con las buenas condiciones para la fabricación de nieve. En general, los años más ventosos también son los más fríos, aunque las estaciones que tienen grandes períodos de frío resultan en frecuencias más bajas de fuertes nevadas e intensas lluvias.

Objetivo 3:

Caracterización de la demanda de turismo de esquí en el Pirineo así como su relación con los componentes meteorológicos, nivológicos y el calendario vacacional.

Conclusiones:

1. La duración de la temporada de esquí en el Pirineo central Aragonés es de 130 días en promedio, pero hay que resaltar una gran variabilidad interanual en la duración de la misma.

2. El momento de apertura y cierre de las estaciones está muy condicionado por el calendario laboral y vacacional siendo el puente de diciembre el momento preferente de apertura y la Semana Santa el momento preferente de cierre de las estaciones con independencia de que se cumplan las condiciones de nieve idóneas.

3. Entre los motivos meteorológicos principales de cierre se encuentra la falta de nieve, el viento excesivo y las nevadas intensas.

4. Existe una gran concentración en la demanda en la temporada, siendo enero y febrero los meses con mayor afluencia. Los fines de semana concentran el 37% del total de los esquiadores de la temporada.

5. En los días laborables la afluencia a pistas está altamente condicionada por las condiciones meteorológicas, mientras que durante los fines de semana la variable climática no es tan determinante.

6. Los días con tiempo ventoso y precipitaciones muestran una afluencia de 2 a 3 veces menor que los días soleados o nublados pero sin viento ni precipitaciones.

7. La afluencia a pistas está también condicionada por el porcentaje kilómetros abiertos. La demanda es tres veces mayor cuando más del 75% de km esquiables estaban abiertos en relación con los momentos en que menos del 25% de la superficie esquiable estaba abierta.

Objetivo 4:

Análisis de la percepción de los esquiadores sobre las diferentes condiciones meteorológicas, el cambio climático y la adaptación de los esquiadores bajo condiciones de nieve deterioradas para el esquí.

Conclusiones:

1. En la valoración que los esquiadores otorgan a las diferentes condiciones meteorológicas y nivológicas para la práctica del esquí, destacan: el hecho de que llueva, haya viento fuerte, la visibilidad sea limitada, o la nieve sea de mala calidad.

Estas situaciones limitarían más la afluencia de esquiadores que los espesores de nieve reducidos.

2. En cuanto a bajo qué condiciones climáticas y nivológicas dejaría de esquiar un día que lo tenía planificado para ello, el 80% de los esquiadores no acudiría en condiciones de lluvia, un 58.5% un día de viento excesivo y un 46% ante mala visibilidad.
3. Ante una situación de malas condiciones de nieve los esquiadores encuestados optarían por: un 49% esquiaría menos a menudo pero siempre que fuera posible en el lugar habitual, un 21% seguiría esquiando con la misma frecuencia aunque hubiera malas condiciones de nieve, un 10% reemplazaría el esquí por otra actividad de montaña y un 8% dejaría de esquiar.
4. El 77% de los encuestados cree que el cambio climático afecta algo a los Pirineos, pero esta percepción disminuye cuando se le pregunta si cree que afecta al turismo de esquí (48%). Sin embargo un 76% de los esquiadores creen que el cambio climático afectará al turismo al esquí en el Pirineo en un escenario futuro.
5. En cuanto a las condiciones nivo-climáticas que más afectadas pueden verse con el cambio climático son según los encuestados: la temperatura, el espesor de nieve y las nevadas.

Objetivo 5:

Impactos a pequeña escala del cambio climático en las condiciones de esquí inducidas por la elevación, la topografía, y la eficacia de la nieve para hacer frente al cambio climático proyectado en los Pirineos.

Conclusiones:

1. La topografía de una estación de esquí, incluyendo la pendiente, la orientación y la elevación es un factor altamente condicionante para la evaluación del impacto del cambio climático en el esquí.

2. Introducir en los análisis de vulnerabilidad la fabricación de nieve artificial es fundamental para un análisis más realista del impacto futuro del aumento de las temperaturas sobre la capa de nieve, ya que es la medida de adaptación más ampliamente utilizada.

3. Las estaciones de esquí analizadas (Arcalís y Formigal) se presentan susceptibles en las orientaciones SE pero viables bajo un escenario +2ºC (excepto la zona más baja de Formigal, dónde no alcanza el umbral de viabilidad aún con el empleo de nieve artificial). Las orientaciones NO de las estaciones analizadas alcanzan el umbral de los 100 días con el uso de nieve artificial.

4. Bajo un escenario de calentamiento más severo (+4ºC) Formigal no alcanza el umbral de viabilidad en ninguna orientación aún con fabricación de nieve artificial. Arcalís muestra alta vulnerabilidad en las orientaciones SE, pero con fabricación de nieve artificial se muestra viable en las orientaciones NO excepto en la cota más baja de la estación.

5. La reducción en el número de días disponibles para el esquí (>30cm espesor) se reduce en Formigal entre un 9% y un 19% en orientaciones NO y un 33%-39% en orientaciones SE bajo un escenario de calentamiento +2°C. El número de días se reduce entre un 40%-72% (NO) y un 84%-93% (SE) bajo un escenario de calentamiento +4°. En todos los casos teniendo en cuenta la fabricación de nieve artificial.

6. La reducción en el número de días disponibles para el esquí (>30cm espesor) se reduce en Arcalís entre un 5% y un 13% en orientaciones NO y un 12%-28% en orientaciones SE bajo un escenario de calentamiento +2°C. El número de días se reduce entre un 13%-44% (NO) y un 41%-61% (SE) bajo un escenario de calentamiento +4°C. En todos los casos teniendo en cuenta la fabricación de nieve artificial.

7. Debido al diferente grado de vulnerabilidad al cambio climático dentro de una misma estación de esquí, las medidas de adaptación deberán ser diferentes y adaptadas especialmente a los condicionantes topográficos en cada caso.

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“La unidad de todas las ciencias se encuentra en la geografía. La importancia de la geografía es que presenta la tierra, como la sede permanente de las ocupaciones del hombre”

John Dewey

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APPENDIX