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Winter tourism under climate change in the Pyrenees and the French Alps: relevance of snowmaking as a technical adaptation

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Abstract. Climate change is increasingly regarded as a threat for winter tourism due to the combined effect of decreasing natural snow amounts and decreasing suitable periods for snowmaking. The present work investigated the snow reliability of 175 ski resorts in France (Alps and Pyrenees), Spain and Andorra under past and future conditions using state-of-the-art snowpack modelling and climate projections using Representative Concentration Pathways RCP2.6, RCP4.5 and RCP8.5. The natural snow reliability (i.e. without snowmaking) elevation showed a significant spatial variability in the reference period (1986–2005) and was shown to be highly impacted by the ongoing climate change. The reliability elevation using snowmaking is projected to rise by 200 to 300 m in the Alps and by 400 to 600 m in the Pyrenees in the near future (2030–2050) compared to the reference period for all climate scenarios. While 99 % of ski lift infrastructures exhibit adequate snow reliability in the reference period when using snowmaking, a significant fraction (14 % to 25 %) may be considered in a critical situation in the near future. Beyond the mid-century, climate projections highly depend on the scenario with either steady conditions compared to the near future (RCP2.6) or continuous decrease in snow reliability (RCP8.5). Under RCP8.5, our projections show that there would no longer be any snow-reliable ski resorts based on natural snow conditions in the French Alps and Pyrenees (France, Spain and Andorra) at the end of the century (2080–2100). For this time period and this scenario, only 24 resorts are projected to remain reliable with snowmaking, all being located in the Alps.

1 Introduction

The ongoing evolution of natural snow conditions related to climate change (Beniston et al., 2018) is increasingly regarded as a major threat for winter tourism (Gilaberte-Burdalo et al., 2014; Steiger et al., 2017; Hoegh-Guldberg et al., 2019). This prompts the question of how climate change affects ski resorts and the relevance of snowmaking as an adaptation measure (Steiger et al., 2017). Initial studies in the early 2000s quantified the snow reliability of ski resorts based on the "100 days" rule, later considered as the reference approach for investigations of climate-induced impacts on the winter tourism (Koenig and Abegg, 1997; Elsasser and Bürki, 2002; Abegg et al., 2007; Steiger, 2010; Pons-Pons et al., 2012; François et al., 2014). This rule states that a ski resort is snow reliable if the snow depth exceeds 30 cm during 100 d or more, which provides objective information when comparing distinct periods (past and future) or locations (Koenig and Abegg, 1997; Elsasser and Bürki, 2002; Abegg et al., 2007; Durand et al., 2009b). The snow reliability line is defined as the elevation above which these conditions are met, allowing the assessment of the reliability of a ski resort by comparing its elevation to the snow reliability line (Koenig and Abegg, 1997; Elsasser and Bürki, 2002; Abegg et al., 2007; Gilaberte-Búrdalo et al., 2017).

Most investigations based on the 100 days rule used single-point representations of ski slopes to assess the snow and meteorological conditions of a given ski resort, often using the median elevation of a ski resort defined as the average of summit and base elevations (Abegg et al., 2007; Scott et al., 2003; Steiger, 2010; Dawson and Scott, 2013; Pons et al., 2015; Gilaberte-Búrdalo et al., 2017). Schmidt et al. (2012) and Rixen et al. (2011) used the "highest", "middle" and "lowest" elevations of the study area while Hennessy et al. (2007) mixed various approaches by considering either a single point or three distinct elevations for each ski resort. Alternatively, Pons-Pons et al. (2012) considered the lowest and highest elevations, between which 75 % of the ski slope surface area was concentrated. These remain coarse representations limiting the analysis of the situation of a ski resort to a binary conclusion of reliable or unreliable (Steiger et al., 2017). Koenig and Abegg (1997) and Elsasser and Bürki (2002) in Switzerland and later Abegg et al. (2007) in the rest of the European Alps based their analysis on the natural snow conditions. Abegg et al. (2007) reviewed the existing literature to address the snow reliability line for regions of Europe (Austria, Italy, Germany, Switzerland and France) based on distinct methods and reference periods (Laternser and Schneebeli, 2003; Wielke et al., 2004; Matulla et al., 2005). They concluded that 91 % of the 666 ski resorts in the European Alps were snow reliable around 2005. Significant spatial variations in the snow reliability line were shown, ranging from 1050 to 1500 m above sea level (a.s.l.) with consequences on local reliability of ski resorts: 69 % of ski resorts were snow reliable in Germany and up to 97 % were snow reliable in Switzerland and France. Abegg et al. (2007) similarly addressed the impact of climate change on the snow reliability line and concluded that under a $+1\,^{\circ}$C warming compared to present only 75 % of European Alps ski resorts would remain reliable and respectively 61 % and 30 % for +2 and $+4\,^{\circ}$C warming compared to the present would remain reliable. These investigations were limited to the analysis of natural snow using average conditions over large regions. Steiger (2010) later showed by the analysis of 52 climate stations in Austria over the 1981–2001 period that an elevation of 1200 m a.s.l. could not be confirmed as snow reliable for all regions of Tyrol (Austria). Using natural snow conditions to assess the snow reliability of ski resorts has also been questioned, due to the strong role of snow management, in particular grooming and snowmaking (Hanzer et al., 2014; Spandre et al., 2016b; Steiger et al., 2017).

Recent studies have increasingly taken into account snow grooming and snowmaking (Scott et al., 2003, 2006; Steiger, 2010; Pons et al., 2015; Steiger et al., 2017). Scott et al. (2003) developed a simple modelling approach accounting for a required snow depth of 50 cm for skiing activities and computed snowmaking requirements based on this target. This method provided consistent season durations for the 1961–1990 reference period in the southern Ontario region (Canada) which were shown to significantly decrease under projected climate conditions despite an increasing need for snowmaking. Scott et al. (2006) later used this modelling approach and a 60 cm snow base depth requirement in the Quebec region (Canada). Steiger and Mayer (2008) applied this method in Tyrol (Austria) and concluded that snowmaking could guarantee snow reliability at elevations above 1000 m a.s.l. for the 1971–2000 reference period and would remain a suitable adaptation method until the 2050s with a significant increase in water and energy requirements (Steiger, 2010). Similar investigations were conducted to assess the impact of climate change on the ski season duration and the snowmaking requirements so as to compensate for the loss in regions of Austria (Marke et al., 2014; Hanzer et al., 2014), Germany (Schmidt et al., 2012), Switzerland (Rixen et al., 2011), Andorra (Pons-Pons et al., 2012), the Pyrenees (Pons et al., 2015; Gilaberte-Búrdalo et al., 2017), the northeastern US (Dawson and Scott, 2013), New Zealand (Hendrikx and Hreinsson, 2012) and Australia (Hennessy et al., 2007). Major limitations remain. First, little investigation was undertaken in France, still a major area for winter tourism (François et al., 2014; Steiger et al., 2017). Second, meteorological and snow input data considered for the analysis were aggregated over large regions (Abegg et al., 2007; Damm et al., 2017) where high spatial variability can be observed (Durand et al., 2009b; François et al., 2014). Third, snow conditions were often simulated using simplified degree day modelling approaches (Dawson and Scott, 2013; Hendrikx and Hreinsson, 2012) and neglected the differences between natural snow and groomed or machine-made snow properties (Pons et al., 2015; Gilaberte-Búrdalo et al., 2017).

The present work aims at producing snow reliability investigations of a wide range of ski resorts in France (Alps and Pyrenees), Spain and Andorra under past and future conditions using state-of-the-art snowpack modelling. We accounted for snow grooming and snowmaking using a detailed snowpack model (Spandre et al., 2016b) and used adjusted and downscaled climate projections from the EURO-CORDEX dataset (Verfaillie et al., 2017, 2018) to compute snow reliability elevations with distinct levels of snow reliability requirements. The mean elevation of residential population in a ski resort (Breiling and Charamza, 1999) and the mean elevation of ski lifts (Falk and Vanat, 2016) were compared to the snow reliability line. We defined seven distinct categories for ski resorts based on their natural snow reliability, their degree of dependence on snowmaking to achieve reliability (Pons et al., 2015) and whether snowmaking may be a technically efficient method to guarantee snow reliability under present and future climate conditions.

2 Method

2.1 Ski resort definition and features

2.1.1 Definition of relevant elevations of ski resorts

All data on the geographical location and technical data on ski resorts were extracted from the "BD Stations" database (François et al., 2014; Spandre et al., 2015). Ski lift installation and operation in France are supervised by the STRMTG ("Services Techniques de Remontées Mécaniques et Transports Guidés"). The STRMTG is a public service in charge of the safety control of French ski lifts providing authorizations for ski lift operations. The STRMTG manages a database (CAIRN: CAtalogue Informatisé des Remontées Mécaniques Nationales) dedicated to ski lifts which includes technical characteristics of each ski lift such as the ski lift power. The ski lift power is an indicator of the size of a ski lift, defined as the product of the elevation difference between the bottom and the top of a ski lift (in kilometres) and its capacity, i.e. the flow of persons per hour (persons h^{-1}), expressed in persons km h^{-1}. Ski lift infrastructures in France have a total ski lift power of 977 000 persons km h^{-1}, 94 % of which are included in the present study (Appendix B). These data are complemented with geographical information from the database BD TOPO (25 m of resolution) developed by the French Geographical Institute (IGN, "Institut Géographique National"). The following elevations were used to be compared with the snow reliability line.

- The mean ski lift elevation of a ski resort is defined as the average of top and bottom elevations of each ski lift weighted by its ski lift power, referred to as the mean elevation of the ski resort (François et al., 2014; Falk and Vanat, 2016).
- The village elevation of a ski resort is defined as the mean elevation of tourism housing infrastructure, where tourists stay during their ski holidays. It is computed using IGN data on the location and characteristics of buildings. Buildings located within 300 m from the bottom of the ski lifts are selected, and the selection procedure continues by iterations, using a 200 m radius around each identified building and so on, until no more buildings are found. We then compute the net floor surface area of each selected building (taking account the number of floors, based on building height), which is used to compute the weighted mean elevation of the built area associated with each resort, weighted by their net floor area (Breiling and Charamza, 1999).

Data for computing the mean ski lift elevation and village elevation of ski resorts using the method described above are only available for France. Another approach was required for addressing the characteristics of ski resorts in Andorra and Spain. Based on the OpenStreetMap (OSM) project (http://www.openstreetmap.org/, last access: 12 April 2019), we estimated the main features for the Spanish and Andorran ski resorts (village elevation, ski lift mean elevation and ski lift power). However, ski lift capacity is not included in OSM, and building height data are incomplete, which hampers our ability to proceed using the method developed for the French ski resorts. To circumvent this issue, we extracted all ski slopes from OSM for all ski resorts in France, Spain and Andorra, and computed linear regressions between information extracted from OSM and independent estimates for French ski resorts, which were then used to compute the indicators for ski resorts in Spain and Andorra (Fig. 1).

- The linear model of the ski lift power versus the OSM surface area (Fig. 1a) had a correlation coefficient $R^2 = 0.87$ (p value $< 10^{-15}$), proving relevant to estimate the ski lift power based on the OSM surface area.
- Elevations derived from the OSM spatial representation also proved significantly correlated to data from the BD Stations (Fig. 1b):
  - All elevations together had a RMSD = 149 m and mean difference = 15 m, and the linear model of slope was 0.97 ($R^2 = 0.91$, p value $< 10^{-15}$).
  - Mean elevation had a RMSD = 154 m and mean difference = 51 m, and the linear model of slope was 0.82 ($R^2 = 0.83$, p value $< 10^{-15}$).
  - The village elevation proved significantly correlated to the mean elevation derived from OSM spatial representations (slope 0.64, intercept 326 m, $R^2 = 0.62$, p value $< 10^{-15}$). The linear model was applied to estimate the village elevation from the OSM mean elevation and compared to the BD Stations data: RMSD = 179 m; mean difference $< 10^{-12}$ (Fig. 1b).

2.1.2 Study area

A sample of 175 ski resorts in the French Alps ($n = 129$), the French Pyrenees ($n = 28$), the Spanish Pyrenees ($n = 14$) and Andorra ($n = 4$) were included in the present study (Fig. 2, Appendix B). The French ski resorts included in this study ($n = 157$) represent 94 % of the national ski lift infrastructures. For Andorra, our study accounts for 100 % of the ski tourism infrastructures. For Spain, there are a total of 30 ski resorts, 14 of which are in the Spanish Pyrenees and considered in this study (note that in our study, the ski resorts La Molina and Masella were considered together). In terms of skiers, the Spanish Pyrenees represent around 63 % of the total ski market in Spain.

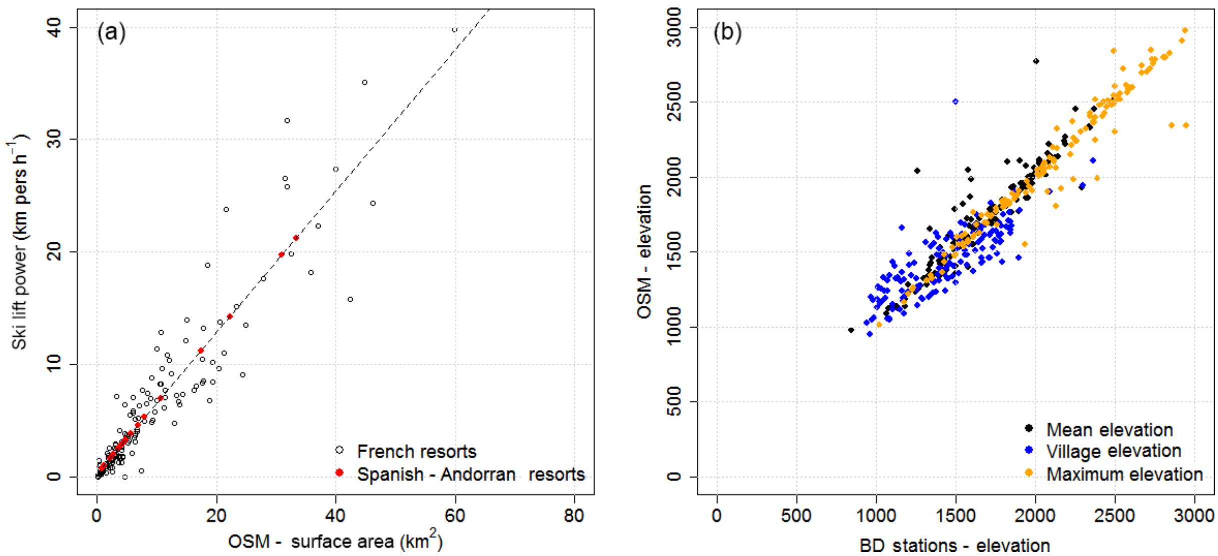

Figure 1. Relationship between OpenStreetMap (OSM) data on French ski resorts and ski lift power (SLP) and elevations of the ski resort (min, mean, max), used to estimate similar indicators in ski resorts in Spain and Andorra. In panel **(b)**, "BD Stations" refers to the database of French ski resorts used in this study (see text for details).

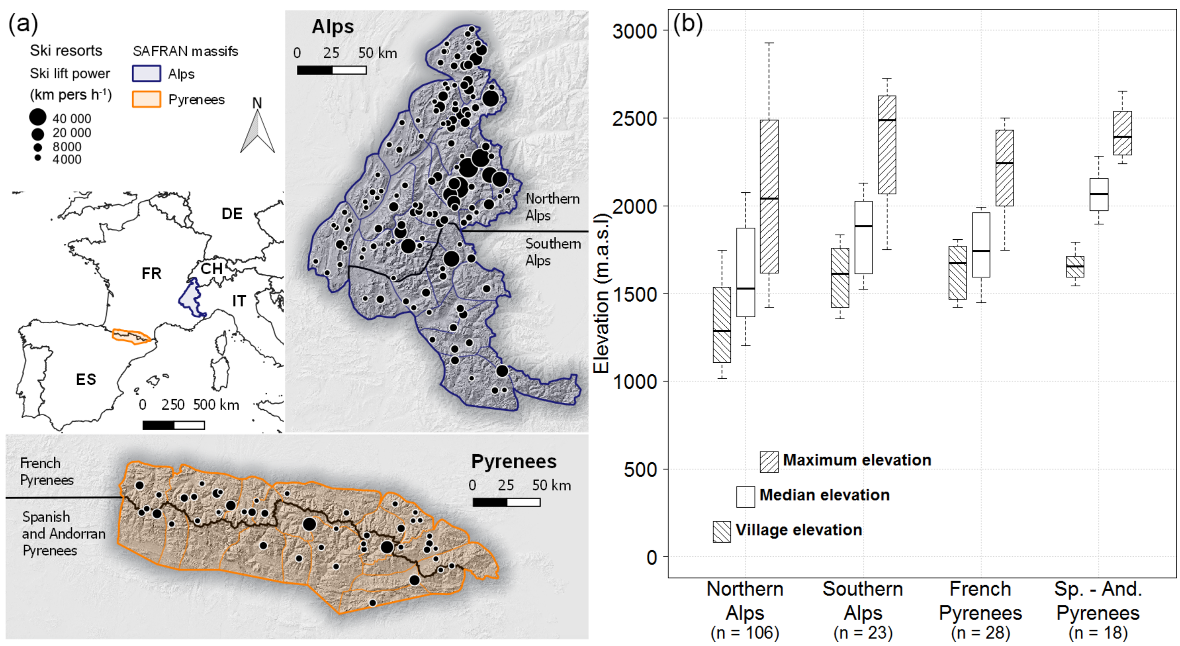

Figure 2. (a) The 175 ski resorts covered by the present study and the 44 massifs from the SAFRAN reanalysis and **(b)** distribution of ski resort elevations depending on their location: northern Alps, southern Alps, French Pyrenees, and Spanish and Andorran Pyrenees ("Sp.–And. Pyrenees"). See Appendix B.

2.2 Definition and computation of the snow reliability line

2.2.1 Snowpack modelling

The "Crocus Resort" version of the multilayer snowpack model SURFEX/ISBA-Crocus was used in the present study (Brun et al., 1992; Vionnet et al., 2012). Crocus Resort allows us to take into account the effect of grooming and snowmaking on snow properties so as to provide simulations of snow conditions on ski slopes (Spandre et al., 2016b). The impacts of grooming are simulated and machine-made snow can be added to the snowpack specifying the precipitation rate (1.2×10^{-3} kg m^{-2} s^{-1}; Spandre et al., 2016a) and conditions for triggering the production (wet-bulb temperature threshold −2 °C, target quantity or target snow depth). The production of snow was based on the following rules, dividing the winter season into distinct periods (Steiger, 2010; Hanzer et al., 2014; Spandre et al., 2016a):

- Between 1 November and 15 December, a 30 cm deep "base layer" (snow mass of $150\,kg\,m^{-2}$, for a typical snow density of $500\,kg\,m^{-3}$) is produced, weather conditions permitting, regardless of natural snowfalls during the period.
- Between 15 December and 28 February, snow is produced, if meteorologically possible, so as to maintain a total snow depth of 60 cm.
- After 1 March, no more snow is produced.

2.2.2 Climate forcing data

The meteorological system SAFRAN (Durand et al., 1993) provides meteorological data (temperature, precipitations, etc.) for mountain areas of an approximate $1000\,km^2$ surface referred to as a "massif", covering the French Alps and Pyrenees, including the Spanish and Andorran Pyrenees (Fig. 2). Within each massif, the meteorological conditions are considered to be homogeneous and to depend only on the elevation (by steps of 300 m) with a time resolution of 1 h. SAFRAN forcing data are available for the 1958–2015 period (Durand et al., 2009a; Durand et al., 2012; Maris et al., 2009). Computations of snow conditions over the reference period using SAFRAN forcing data are further referred to as "SAFRAN" and can be considered as the reference observational dataset.

This study uses the EURO-CORDEX dataset (Jacob et al., 2014; Kotlarski et al., 2014) for climate projections consisting of six regional climate models (RCMs) forced by five different global climate models (GCMs) from the CMIP5 ensemble (Taylor et al., 2012) over Europe, for the historical, RCP2.6, RCP4.5 and RCP8.5 scenarios (Moss et al., 2010). All EURO-CORDEX data were adjusted using the ADAMONT method (Verfaillie et al., 2017) using the SAFRAN data as the reference observation dataset (Verfaillie et al., 2018). Historical runs generally cover the period 1950–2005 and climate projections (RCPs) cover the period 2006–2100 (Table 1). Continuous hourly resolution meteorological time series derived from RCM output by the ADAMONT statistical adjustment method are then used as input of the SURFEX/ISBA-Crocus snowpack model (Verfaillie et al., 2017, 2018).

2.2.3 Snow indicators

The snow reliability line was computed from the simulated snow conditions for the reanalysis and all GCM–RCM pairs and scenarios. The snow reliability line was based on the 100 days rule and defined for a given season as the elevation above which a minimum quantity of $100\,kg\,m^{-2}$ of snow (i.e. 20 cm of snow at $500\,kg\,m^{-3}$ density) was simulated during at least 100 d between 15 December and 15 April (Scott et al., 2003; Steiger, 2010; Marke et al., 2014; Pons et al., 2015). The use of snow mass instead of snow depth (Marke et al., 2014) appeared more relevant for our study, considering the differences between natural snow properties and machine-made snow or groomed snow (Spandre et al., 2016b). Based on the season length computed for SAFRAN massif elevations (300 m step), a linear interpolation was used to compute the snow reliability line meeting the 100 d threshold. In cases where the season length at the minimum (respectively maximum) elevation was longer (respectively shorter) than 100 d, the snow reliability line was set to half the altitudinal step (150 m) below (respectively above) the minimum (respectively maximum) elevation for a given massif. We further computed for each massif the snow reliability line by considering distinct periods, climate scenarios, snow requirements and snow management, providing 48 distinct values of the snow reliability elevation resulting from the combination of these parameters (Tables A1, A2, A3 in Appendix). Eight periods and scenario configurations are based on the reference period (1986–2005) using the SAFRAN reanalysis and available GCM–RCM pairs (HIST), the near future (2030–2050) and the end of the century (2080–2100), using climate scenarios RCP2.6, RCP4.5 and RCP8.5 for all available GCM–RCM pairs (Table 1). Three distinct levels of snow reliability requirements were defined as the elevation where the season length reached 100 d one season out of two (50 % percentile of annual values), seven seasons out of 10 (70 % percentile of annual values) and nine seasons out of 10 (90 % percentile of annual values). Last, we considered the groomed snow conditions (no snowmaking) and including snowmaking (two configurations). We did not compute indicators based on unmanaged natural snow conditions alone, i.e. without grooming or snowmaking.

2.3 Definition of snow reliability categories

Seven snow reliability categories have been designed with respect to the natural snow reliability and the relevance of snowmaking as an efficient adaptation method to reduce the effect of snow variability and scarcity, in line with previous investigations (Pons et al., 2015; Steiger and Mayer, 2008). Following Steiger and Mayer (2008), we considered a strict threshold of nine winters out of 10 for snowmaking reliability (90 % percentile of annual values), considering that snowmaking facilities are an investment for the operations of ski resorts and should therefore target a high level of reliability. The following categories were defined to characterize the snow reliability of ski resorts, depending on the relationship between village elevation and mean ski lift elevation, and the reliability lines with and without snowmaking. The village elevation is critical because this corresponds to the entry point of skiers to the ski slopes from their tourism housing in-

Table 1. EURO-CORDEX GCM–RCM combinations used in this study (rows: RCMs; columns: GCMs), with the time period available for the HIST and RCP4.5 and RCP8.5 scenarios (RCPs). Model combinations additionally using RCP2.6 are displayed in bold. Contributing institutes are indicated inside parentheses – CLMcom: Climate Limited-area Modelling Community with contributions by BTU, DWD, ETHZ, UCD,WEGC; CNRM: Météo France; IPSL-INERIS: Institut Pierre Simon Laplace, CNRS, France – Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA/CNRS/UVSQ – Institut National de l'Environnement Industriel et des Risques, Verneuil en Halatte, France; KNMI: Kingdom of Netherlands Meteorological Institute, Ministry of Infrastructure and the Environment; MPI-CSC: Max Planck Institute for Meteorology, Climate Service Center, Hamburg, Germany; SMHI: Swedish Meteorological and Hydrological Institute, Rossby Centre, Norrköping, Sweden.

RCM (institute)–GCM	Period	CNRM-CM5	EC-EARTH	HadGEM2-ES	MPI-ESM-LR	IPSL-CM5A-MR
CCLM 4.8.17 (CLMcom)	HIST	1950–2005	1950–2005	1981–2005	1950–2005	
	RCPs	2006–2100	2006–2100	2006–2099	2006–2100	
ALADIN 53 (CNRM)	HIST	1950–2005				
	RCPs	**2006–2100**				
WRF 3.3.1F (IPSL-INERIS)	HIST					1951–2005
	RCPs					2006–2100
RACMO 2.2E (KNMI)	HIST			1981–2005		
	RCPs			**2006–2099**		
REMO 2009 (MPI-CSC)	HIST				1950–2005	
	RCPs				2006–2100	
RCA 4 (SMHI)	HIST	1970–2005	1970–2005	1981–2005	1970–2005	1970–2005
	RCPs	2006–2100	**2006–2100**	2006–2099	2006–2100	2006–2100

frastructure. This often corresponds to the lower elevation of the major ski lift infrastructure, which is a key area for snow managers because snow reliability there is both challenging and a strong asset for the ski resort operations (Spandre et al., 2016a). Categories are ordered by decreasing levels of natural and managed snow reliability. For each ski resort, its category corresponds to the first one for which the criterion is fulfilled, from category 1 until category 7. A ski resort fulfilling the condition of category N-1 also fulfills the condition of category N. Ski resorts in category N fulfill the condition of category N but not the condition of category N-1.

- Category 1: village elevation above the 90 % groomed snow reliability line.
- Category 2: village elevation above the 70 % groomed snow reliability line and village elevation above the 90 % snowmaking reliability line.
- Category 3: mean ski lift elevation above the 70 % groomed snow reliability line and village elevation above the 90 % snowmaking reliability line.
- Category 4: mean ski lift elevation above the 50 % groomed snow reliability line and village elevation above the 90 % snowmaking reliability line.
- Category 5: village elevation above the 90 % snowmaking reliability line.
- Category 6: mean ski lift elevation above the 90 % snowmaking reliability line.
- Category 7: mean ski lift elevation below the 90 % snowmaking reliability line.

Categories 1, 2 and 3 illustrate ski resorts where natural snow conditions are generally reliable (Abegg et al., 2007; Scott et al., 2003; Pons et al., 2015). Snowmaking is generally employed only at the lowest elevations, and it makes a difference only for a minority of seasons when natural snow conditions are too scarce. Categories 4 and 5 illustrate ski resorts where natural snow conditions may not be considered as reliable as the previous categories, but snowmaking can generally guarantee the reliability in all elevations of the resort. In these two categories, snowmaking is useful and efficient in reducing natural snow scarcity at all elevations of the resort (Pons et al., 2015). Categories 6 and 7 illustrate ski resorts where natural snow conditions are generally not considered reliable and snowmaking is not efficient in reducing natural snow scarcity at the lowest elevations of the resort.

3 Results

3.1 Snow conditions and snow reliability line

3.1.1 Past climate conditions

Figure 3 shows that a significant spatial variability of the snow reliability line can be observed for the reference period (1986–2005). The median elevation of the 70 % groomed snow reliability ranges between 1750 m a.s.l. in the northern

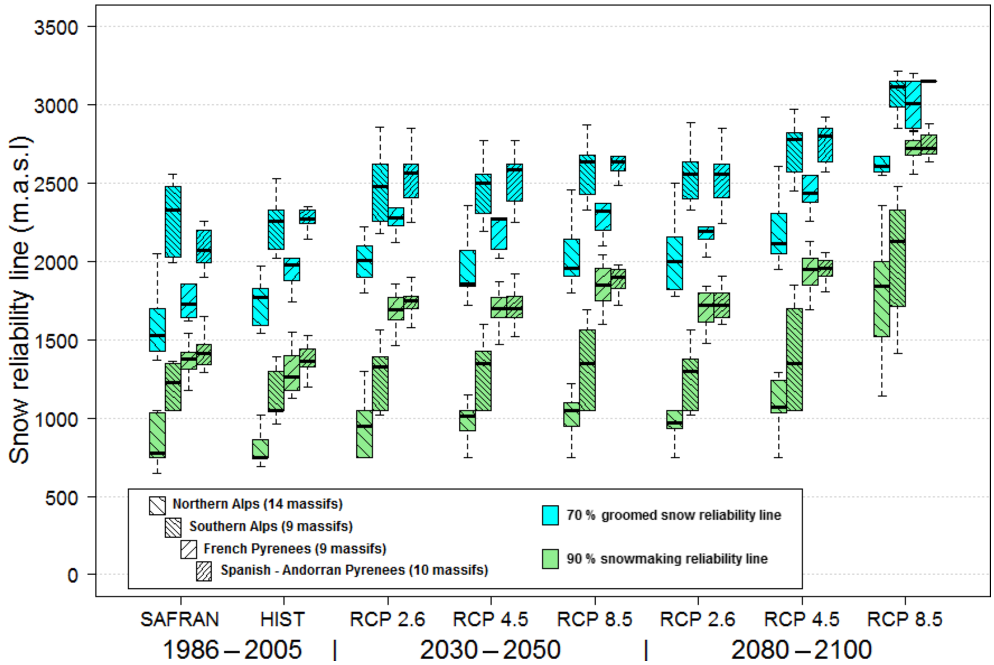

Figure 3. Spatial variability between massifs and evolution for the reference period, the near future (2030–2050) and the end of the century (2080–2100) of the snow reliability line based on RCP2.6, RCP4.5 and RCP8.5 for the main areas covered in the present study (northern and southern Alps, French and Spanish–Andorran Pyrenees).

Alps, 2000 m a.s.l. in the French Pyrenees, 2250 m a.s.l. in the southern Alps, and up to 2300 m a.s.l. in the Spanish and Andorran Pyrenees (HIST, Fig. 3). Although a deviation can be observed, the spatial variability is consistent between climate model computations over the reference period (HIST) and the reference dataset (SAFRAN). The 90 % snow reliability using snowmaking is significantly lower than the 70 % groomed snow reliability line (Fig. 3). Due to snowmaking the median reliability elevation increases between 700 m in the French Pyrenees, 900 m in the Spanish and Andorran Pyrenees, 1000 m in the northern Alps, and up to 1200 m in the southern Alps. This results in a snowmaking reliability line significantly lower in the southern Alps compared to the Pyrenees despite poorer natural snow conditions (Fig. 3). Although the improvement of snow conditions thanks to snowmaking is lower in the Pyrenees compared to the Alps, the annual snowmaking requirements are higher, with 400 to 550 $kg\,m^{-2}$ machine-made snow produced at the snow reliability line in the northern and southern Alps (10 %–90 % percentiles of annual values) and 400 to 700 $kg\,m^{-2}$ in the French, Spanish and Andorran Pyrenees (HIST). Such production is equivalent to 80 cm to 1.1 m of snow in the Alps and 80 cm to 1.4 m of snow in the Pyrenees at the snow reliability line (using a machine-made snow density value of 500 $kg\,m^{-3}$).

3.1.2 Future change in the near future (2030–2050)

Natural snow conditions are projected to be significantly affected by climate change in the near future (2030–2050) with similar evolution between climate scenarios (Fig. 3). The median 70 % groomed snow reliability line is projected to range between

- 1850 and 2000 m a.s.l. in the northern Alps (100 to 250 m above the reference period);
- 2500 and 2650 m a.s.l. in the southern Alps (200 to 400 m above the reference period);
- 2250 and 2300 m a.s.l. in the French Pyrenees (300 to 350 m above the reference period);
- 2550 and 2650 m a.s.l. in the Spanish and Andorran Pyrenees (300 to 350 m above the reference period).

Due to the combined effect of decreasing natural snow conditions and decreasing suitable conditions for snowmaking, the 90 % snow reliability line using snowmaking is projected to rise by 200 to 300 m in the northern Alps, 300 m in the southern Alps and up to 400 to 600 m in the Pyrenees compared to the reference period. In the near future the median elevation of the snowmaking reliability is projected to range between 950 and 1050 m a.s.l. in the northern Alps, 1350 m a.s.l. in the southern Alps, 1700 to 1850 m a.s.l. in the French Pyrenees, and 1750 to 1900 m a.s.l. in the Spanish and Andorran Pyrenees. The production of machine-made snow at the snow reliability line is projected to remain steady or to decrease in the Pyrenees, up to 15 % compared to the reference period. In the Alps, the production of machine-made snow is projected to increase for all scenarios up to 15 %. This highlights the higher suitability of climate conditions for snowmaking in the Alps compared to the Pyrenees and increases the gap in the elevation of the snowmaking reliability between these areas (Fig. 3).

3.1.3 Future change at the end of the century (2080–2100)

The impact of climate change on natural snow conditions beyond the mid-century is projected to be highly dependent on the climate scenario. Conditions at the end of the century (2080–2100) are projected to remain similar to those in the near future, for RCP2.6, with the median 70 % groomed snow reliability line ranging between 200 and 300 m above the elevation for the reference period. Under RCP8.5, this elevation at the end of the century would be 850 m higher than the value for the reference period in the northern and southern Alps, 900 m in the Spanish and Andorran Pyrenees, and up to 1050 m in the French Pyrenees.

The snowmaking reliability elevation is projected to suffer from the decrease in periods suitable for snowmaking. The median elevation at the end of the century is projected to be 200 m (northern Alps) to 450 m (French Pyrenees) higher than the value for the reference period for RCP2.6 and up to 1100 m (northern and southern Alps) to 1450 m (French Pyrenees) higher for RCP8.5. The median elevation of the reliability using snowmaking for RCP8.5 is projected to range at the end of the century between 1850 m a.s.l. in the northern Alps, 2150 m a.s.l. in the southern Alps, and 2700 m a.s.l. in the French, Spanish and Andorran Pyrenees (Fig. 3).

In the Pyrenees, the production of machine-made snow is projected to decrease by 15 % to 35 % in the French Pyrenees and 10 % to 20 % in the Spanish and Andorran Pyrenees (10 %–90 % percentiles) compared to the reference period due to the lack of suitable conditions. In the Alps, snowmaking is projected to remain relatively steady at the snow reliability elevation compared to the near future with higher requirements compared to the reference period up to 10 %.

3.2 Snow reliability of ski resorts

3.2.1 Past climate conditions

Figures 3 and 4 and Table 2 show a deviation between the SAFRAN reference dataset and results derived from climate models (HIST) for the reference period. We therefore focus our analysis on the comparison of snow conditions computed by climate models for the reference and future periods. Based on climate models, ski lift infrastructures were reliable during the reference period (1986–2005), with either natural snow conditions (50 % in categories 1, 2 and 3 altogether; Table 2, HIST) or with snowmaking (49 % in categories 4 and 5 altogether). Natural snow conditions in larger ski resorts were more reliable than in the smaller ones with 44 resorts representing 50 % of the ski lift power being reliable using natural snow only and 129 ski resorts also representing 49 % of the ski lift power being only reliable with snowmaking (Table 2). Categories 6 and 7 include resorts where 90 % snowmaking reliability can not be achieved at the elevation of the village (category 6) or at the mean ski lift elevation (category 7). These categories represent the situation of a marginal fraction of ski resorts in the reference period: less than 1 % unreliable facilities (two resorts in these categories) and might therefore be considered in a critical situation in terms of snow conditions. Figures 4 and 5 also illustrate a significant geographical pattern with most naturally snow-reliable ski resorts being located in the northern Alps and central Pyrenees. This can be related to the lower elevation of the snow reliability line in the northern Alps compared to the southern Alps or the Pyrenees (Fig. 3, Appendix A1) and the higher elevation of larger ski resorts, most of them being located in the northern Alps and central Pyrenees (Figs. 2 and 5). The variability is particularly high between the northern Alps (a majority of ski resorts were naturally snow reliable: 67 % of ski lift power) and the southern Alps (89 % were reliable with snowmaking) highlighting a higher dependence of southern Alps ski resorts on snowmaking in the reference period (only 12 % of ski lift power was naturally snow reliable). The situation of the Pyrenees ski resorts lies in between (Fig. 5).

3.2.2 Future change in the near future (2030–2050)

In the near future (2030–2050) and depending on the RCP, only 14 to 24 ski resorts (21 % to 32 % of ski lift power) are projected to remain snow reliable based on natural conditions, all being located in the northern Alps except one in the central Pyrenees (Table 2). An additional 83 to 116 resorts (representing 49 % to 64 % of ski lift power) are projected to remain reliable with snowmaking. Overall, a majority of ski resorts would remain reliable, either with snowmaking or under natural snow conditions (75 % to 86 % of ski lift power). A significant fraction of 45 to 75 ski resorts (14 % to 25 % of ski lift power) would however turn either into category 6 (12 % to 18 % of ski lift power) or even category 7 (2 % to 7 % of ski lift power) where 90 % snowmaking reliability can not be achieved at the elevation of the village (category 6) or at the mean ski lift elevation (category 7). The geographical pattern identified for past climate conditions is projected to remain in the near future. Even though there would not be any naturally snow-reliable ski resort in the southern Alps, snow conditions are projected to remain reliable with snowmaking for most resorts (reduction from 100 % to 89 % of reliable with snowmaking ski lift power), displaying a consistent distribution between reliability categories compared to the reference period (Fig. 4). Conversely, the projected im-

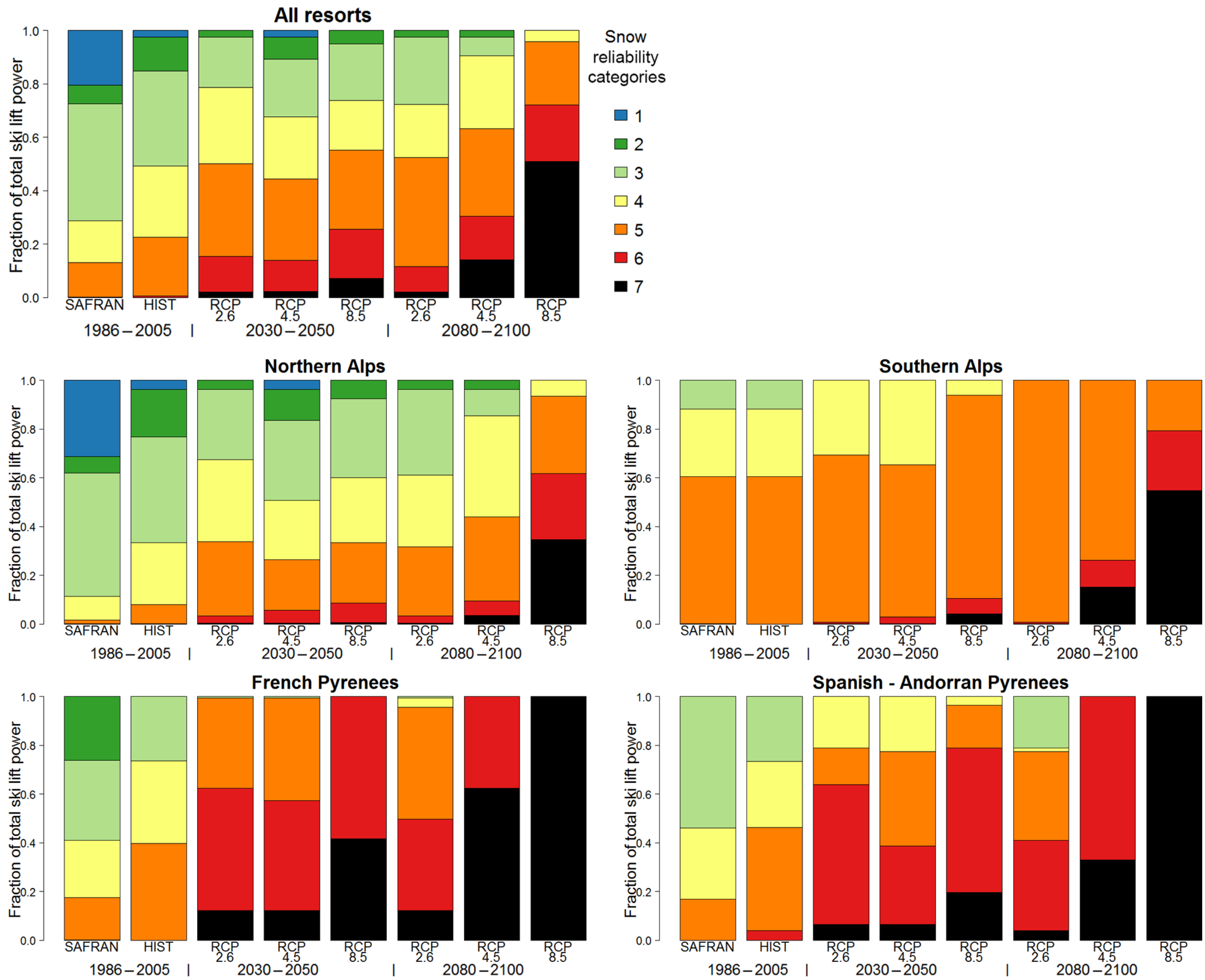

Figure 4. Distribution of the total ski lift power (%) within reliability categories for distinct periods and scenarios (Table 2).

pact on the Pyrenees ski resorts is significant, particularly in the French Pyrenees. There would remain a single naturally snow reliable resort, but more important is the fraction of resorts turning into category 6 (45 % to 58 % of ski lift power in the French Pyrenees and 32 % to 59 % in the Spanish and Andorran Pyrenees) or even category 7 (12 % to 42 % of ski lift power in the French Pyrenees and 7 % to 20 % in the Spanish and Andorran Pyrenees).

3.2.3 Future change at the end of the century (2080–2100)

Beyond the near future, the evolution of snow conditions strongly depends on the climate scenario, due to both the evolution of natural snow conditions and the availability of suitable periods for snowmaking (Fig. 3). According to the scenario RCP2.6, snow reliability is projected to remain similar or even improve at the end of the century (2080–2100) compared to the near future (2030–2050). Figures 3 and 4 and Table 2 illustrate the significant impact of climate change on the snow conditions and ski resort reliability for RCP8.5 compared to the two other scenarios. Our projections indicate that there would not remain any ski resort with reliable natural snow conditions based on RCP8.5, with only 24 ski resorts (28 % of ski lift power) benefiting from snowmaking reliability (Table 2), all of them being located in the Alps. Figure 4 illustrates a strong geographical pattern within the Alps with higher snow reliability in eastern central Alps compared to external and southern massifs. End of century RCP8.5 ski resorts reliable with snowmaking are projected to be located in Vanoise ($n = 7$), Haute-Tarentaise ($n = 5$), Maurienne ($n = 5$) and Haute-Maurienne ($n = 3$) in the northern Alps, and Thabor ($n = 1$), Pelvoux ($n = 1$), Queyras ($n = 1$) and Champsaur ($n = 1$) in the southern Alps.

Table 2. Distribution of the total ski lift power (%) within reliability categories for distinct periods and scenarios (Fig. 4) with the corresponding number of ski resorts (n).

	Reference (1986–2005)		Near future (2030–2050)			End of the century (2080–2100)		
Category	SAFRAN	HIST	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
1	21 ($n=11$)	2 ($n=2$)	0	2 ($n=2$)	0	0	0	0
2	7 ($n=15$)	13 ($n=7$)	2 ($n=2$)	8 ($n=3$)	5 ($n=3$)	2 ($n=2$)	2 ($n=2$)	0
3	44 ($n=53$)	35 ($n=35$)	19 ($n=12$)	22 ($n=19$)	21 ($n=14$)	25 ($n=16$)	7 ($n=4$)	0
4	16 ($n=42$)	27 ($n=51$)	29 ($n=25$)	23 ($n=24$)	19 ($n=19$)	20 ($n=23$)	27 ($n=20$)	4 ($n=2$)
5	13 ($n=50$)	22 ($n=78$)	35 ($n=91$)	31 ($n=81$)	30 ($n=64$)	41 ($n=90$)	33 ($n=63$)	24 ($n=22$)
6	0 ($n=4$)	1 ($n=2$)	13 ($n=31$)	12 ($n=29$)	18 ($n=39$)	10 ($n=28$)	16 ($n=35$)	21 ($n=21$)
7	0	0	2 ($n=14$)	2 ($n=17$)	7 ($n=36$)	2 ($n=16$)	14 ($n=51$)	51 ($n=130$)

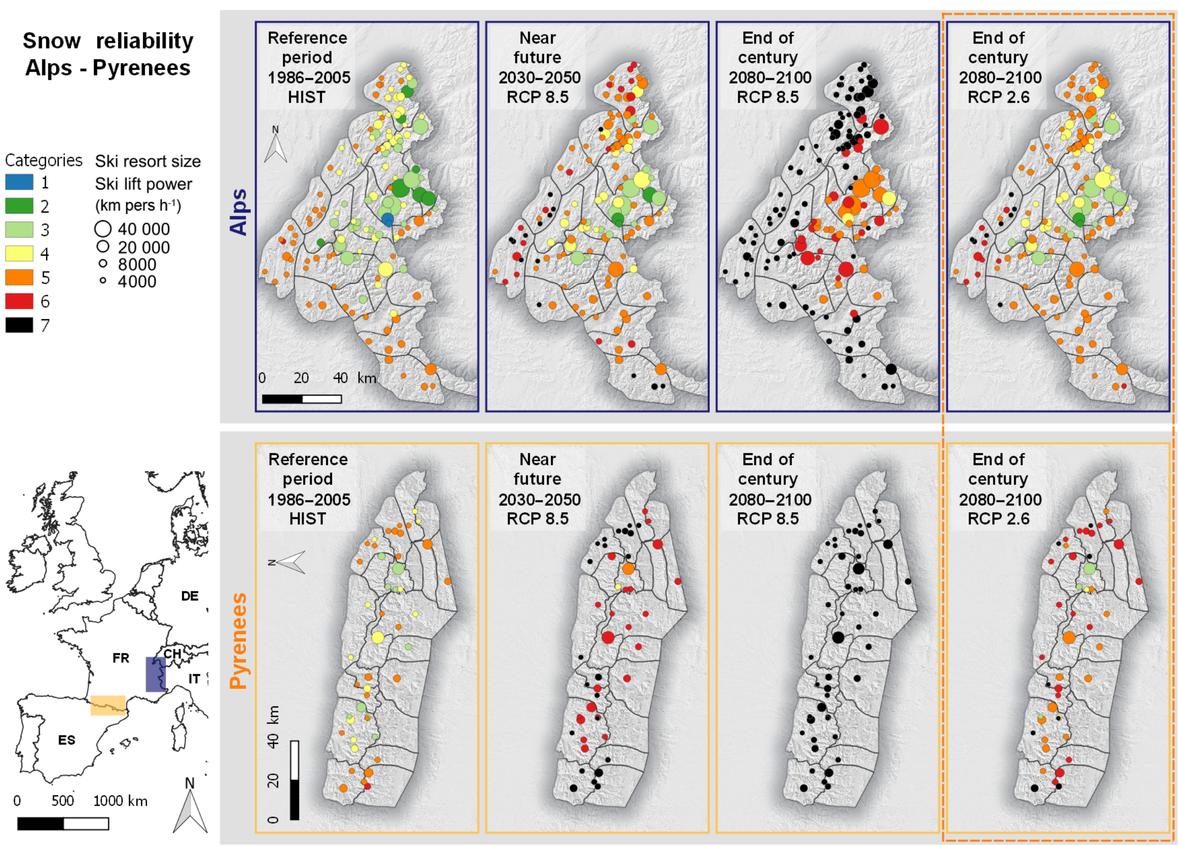

Figure 5. Fraction of ski lift power (%) for a given category (Sect. 2.3). Categories 1, 2 and 3 illustrate ski resorts where natural snow conditions are reliable. Categories 4 and 5 illustrate ski resorts where snow conditions are reliable with snowmaking. Categories 6 and 7 illustrate ski resorts where snowmaking is no longer efficient in reducing the effect of natural snow scarcity at the lowest elevations of the resort.

4 Discussion

A number of limitations remain in our approach and should be carefully considered in the interpretation of our results. Concerning the modelling of the snowpack evolution under past and future climate conditions, meteorological forcing data are aggregated at the scale of a massif (an approximately 1000 km^2 surface area) and by elevation steps of 300 m, which is a significant improvement compared to previous investigations (Abegg et al., 2007; Damm et al., 2017) although local effects are still neglected. The snow melting rate is probably underestimated in the model leading to somewhat optimistic results (Spandre et al., 2016b). The main reason for this is the one-dimensional assumption in the snowpack model neglecting the snow–ground partitioning, particularly when the natural snow melts out and leaves the ski slope as an isolated snow patch in grass or rock fields (Mott et al., 2015). This situation is likely to be more frequent under future climate conditions, resulting in increasingly optimistic results compared to the reference period. Additionally, all results computed based on the observational reference dataset and climate models exhibit differences in the reference period (Figs. 3 and 4 and Table 2). Discrepancies may be due to potential biases of the multivariate distribution of the meteorological variables produced by the adjustment and downscaling method (Verfaillie et al., 2017). This could result in potential nonlinear effects due to multiple dependencies, especially on temperature, relative humidity, precipitation and wind speed.

Beyond the modelling of snow conditions, the main limitations pertain to the snow reliability line approach. Single-point representations are considered on a flat field, i.e. neglecting the aspect and slope angles of a given ski area, which is of high importance in the seasonal evolution of the snowpack and might highly differ from one resort to another. These representations also neglect that all slopes are not covered by snowmaking facilities, hampering any detailed investigation of the evolution of water requirements (results are limited to values per unit surface area). Modelling chains including spatial representations of ski resorts may overcome such weaknesses of the snow reliability line approach (Spandre et al., 2018). Additionally, even though snowmaking may appear to be an efficient method to technically reduce the impacts of natural snow scarcity, the attractiveness of a given resort may be damaged due to either the lack of snow in parts of the ski resort not equipped with facilities or even the lack of natural snow (landscapes, winter spirit).

We provided information beyond a binary assessment of reliable or unreliable by creating reliability categories, although economic implications should be specifically investigated with a more detailed approach. For example, the relative economic importance of specific periods (Christmas and Winter school holidays) is also neglected in this approach, similarly to previous uses of the snow reliability line. More importantly, our study highlights ski resorts which, under present climate conditions, exhibit challenging snow reliability indicators (category 5 ski resorts in outer northern Alps regions, the southernmost southern Alps, and the eastern and western parts of the Pyrenees), but are currently operational. This indicates that snow reliability is only one factor of the socio-economic performance of ski resorts. This corroborates that the assessment of the sustainability of winter ski tourism destinations must encompass dimensions other than snow conditions alone, consistent with earlier findings (Luthe et al., 2012).

5 Conclusion

State-of-the-art snowpack modelling and climate projections were used in the present investigation to provide a snow reliability assessment of a large sample of 175 ski resorts in the French Alps and Pyrenees (France, Andorra and Spain) under past and future climate conditions. We report on a significant spatial variability in snow reliability, with or without snowmaking. The northern Alps showed the best natural snow conditions for the reference period (1986–2005) and under future climate conditions. Snowmaking appears to be an efficient method to improve the snow reliability with 99 % of ski lift facilities reliable with snowmaking for the reference period. This is particularly true in the southern Alps where snowmaking leads to a lower elevation of the snowmaking reliability compared to the Pyrenees, while the natural snow reliability line is higher. This situation is projected to remain in future climate conditions and snow reliability elevation is projected to significantly rise due to the decrease in natural snow conditions and the suitable conditions for snowmaking. The difference between projected deviation between climate scenarios is very low in the near future (2030–2050). Depending on the RCP, 21 % to 32 % of ski lift infrastructures would remain reliable based on natural snow conditions while another 14 % to 25 % might be considered in a critical situation, i.e. for which snowmaking reliability can not be achieved. Significant snowmaking requirements are projected to be necessary at the snow reliability line ranging between 400 and 700 $kg\,m^{-2}$, i.e. an equivalent 80 to 140 cm of machine-made snow production. Deviations between climate scenarios only appear after the mid-century with limited changes compared to the near future (RCP2.6) or continuous decrease in the snow reliability (RCP8.5). At the end of the century and for RCP8.5, our projections indicate that there would not remain any reliable resort based on natural snow conditions and only 24 resorts (28 % of ski lift facilities) would benefit from snowmaking reliability, all being located in the Alps.

The past and future snow reliability of ski resorts in the French Alps and Pyrenees is highly variable, and the present investigation illustrates the relevance of considering local situations rather than drawing general conclusions. We believe that our results might be substantial material for discussions of the relevance of snowmaking as a technical adaptation and the decision-making regarding investments in these facilities. Management implications and economic issues might also be derived from this approach, which should be extended to mid-elevation areas in France (Jura, Vosges, Massif Central). This also bears potential for wider extension including at the European scale taking advantage of the fact that the method does not require complex data to characterize ski resorts (village and mean ski lift elevation) and could be applied to simulations of natural and managed snow at the European scale (Morin et al., 2018).

Assessing the impact of climate change on the ski tourism economy requires not only an estimate of future changes of natural and managed snow conditions, which we provided here, but also additional information on water requirements for snowmaking and how it affects the environmental context and business model of the ski industry. While until the mid-21st century snowmaking appears to be an efficient adaptation option to reduce the climate change hazard to ski resort operating conditions, their environmental footprint and socio-economic functioning may be altered, thereby increasing the vulnerability dimension of the socio-ecological risk if the mountain tourism business model remains unchanged. Towards the end of the century, under high-emission climate change scenarios (RCP8.5), the snow reliability will severely be questioned for most ski resorts currently operating in the Pyrenees and the French Alps, with and without snowmaking, with increased climate change risk under the current mountain tourism business model. Regardless of the time period of interest, future studies are required to analyse and assess all dimensions of climate change impacts and risk to this key mountain economic sector, in France and many other places on Earth.

Data availability. The climate projections used in this study are available on the Drias portal: http://drias-climat.fr/ (last access: 24 April 2019). Model results are available upon request to the corresponding author.

Appendix A: Snow reliability elevation

A1 Reference period (1986–2005)

Table A1. Snow reliability elevation for the reference period (1986–2005) for the 42 massifs distributed over the northern Alps, southern Alps, French Pyrenees, and Spanish and Andorran Pyrenees, computed by the reference dataset (SAFRAN) and the climate models (HIST) for three distinct reliability requirements (50 %, 70 % and 90 %).

	Groomed snow						Including snowmaking					
	SAFRAN (quantiles)			HIST (quantiles)			SAFRAN (quantiles)			HIST (quantiles)		
Massif	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %
Northern Alps												
Chablais	1240	1410	1630	1350	1580	1940	450	670	930	450	630	780
Aravis	1220	1370	1620	1310	1540	1910	750	750	750	750	750	750
Mont Blanc	1160	1390	1580	1350	1580	1930	1050	1050	1050	1050	1050	1050
Bauges	1190	1440	1670	1340	1590	1970	450	450	650	450	450	730
Beaufortain	1270	1430	1660	1350	1620	2100	750	750	750	750	750	750
Haute-Tarentaise	1450	1560	1720	1470	1800	2280	750	750	750	750	750	750
Chartreuse	1310	1490	1740	1420	1830	2070	450	680	770	450	650	860
Belledonne	1380	1510	1650	1420	1650	1960	450	650	770	450	450	750
Maurienne	1450	1550	1740	1420	1740	2160	450	620	780	450	450	690
Vanoise	1490	1690	1780	1460	1830	2230	750	750	750	750	750	750
Haute-Maurienne	1910	2050	2480	2070	2270	2520	1050	1050	1050	1050	1050	1050
Grandes-Rousses	1660	1790	2170	1700	1940	2440	750	750	780	750	750	750
Vercors	1490	1700	1860	1580	1800	2150	620	850	1050	640	790	1020
Oisans	1690	1870	2230	1740	1970	2320	750	800	1030	750	750	770
Southern Alps												
Thabor	1820	2040	2590	1850	2060	2470	1350	1350	1350	1350	1350	1350
Pelvoux	1630	2010	2690	1800	2020	2430	1050	1050	1050	1050	1050	1050
Queyras	2150	2480	2940	2210	2370	2790	1050	1050	1050	1050	1050	1050
Dévoluy	1820	2030	2470	1840	2090	2470	780	1100	1280	750	900	1160
Champsaur	1680	1990	2540	1850	2080	2510	1050	1050	1050	1050	1050	1050
Embrunnais Parpaillon	2110	2520	2960	2040	2260	2810	750	940	1170	750	750	960
Ubaye	2250	2560	2940	2300	2530	2910	1050	1050	1230	1050	1050	1050
Haut-Var Haut-Verdon	2140	2330	2580	2060	2280	2690	960	1230	1350	900	1080	1300
Mercantour	2210	2360	2760	2100	2330	2740	1050	1280	1360	1050	1240	1390
French Pyrenees												
Aspe Ossau	1480	1620	1930	1740	1970	2210	960	1050	1400	1080	1220	1400
Haute-Bigorre	1670	1730	1950	1770	1980	2220	970	1060	1380	910	1080	1260
Aure Louron	1630	1860	1940	1830	2010	2270	930	990	1310	850	980	1210
Luchonnais	1650	1830	2020	1860	2020	2280	890	960	1420	750	900	1180
Couserans	1430	1620	1770	1560	1740	2050	900	1000	1180	800	930	1130
Haute-Ariège	1490	1640	1760	1690	1850	2140	890	970	1240	800	940	1130
Orlu St-Barthélémy	1580	1680	1800	1720	1880	2240	1050	1230	1310	1060	1170	1330
Capcir-Puymorens	2050	2380	2580	2320	2570	2850	1200	1310	1540	1050	1260	1530
Cerdagne-Canigou	2180	2360	2710	2320	2600	3000	1180	1310	1600	1180	1310	1550
Spanish and Andorran Pyrenees												
Andorra	1790	1990	2370	1930	2100	2530	920	1130	1290	860	1080	1290
Jacetania	1860	1930	2010	2010	2140	2340	1180	1280	1470	1170	1350	1530
Gallego	1780	1900	2040	2060	2240	2440	1110	1160	1360	1110	1240	1470
Esera	2050	2260	2360	2150	2290	2560	1040	1170	1590	840	1020	1340
Aran	1950	2070	2200	2080	2330	2630	1020	1140	1460	920	1110	1330
Ribagorçana	1960	2200	2350	2110	2300	2650	1070	1150	1340	890	1070	1340
Pallaresa	1900	2150	2450	2040	2260	2640	930	1050	1300	750	950	1200
Ter-Freser	2060	2570	2810	2060	2350	2780	1250	1320	1650	1130	1290	1440
Cadi Moixero	2010	2070	2450	2280	2530	2850	1060	1170	1460	980	1180	1380
Pre-Pyrenees	1960	2060	2250	2190	2250	2250	1020	1230	1370	980	1180	1420

A2 Near future (2030–2050)

Table A2. Snow reliability elevation for the near future (2030–2050) for the 42 massifs distributed over the northern Alps, southern Alps, French Pyrenees, and Spanish and Andorran Pyrenees, computed by climate models for the RCP2.6, RCP4.5 and RCP8.5 and for three reliability requirements (50 %, 70 % and 90 %).

	Groomed snow									Including snowmaking								
	RCP2.6 (quantiles)			RCP4.5 (quantiles)			RCP8.5 (quantiles)			RCP2.6 (quantiles)			RCP4.5 (quantiles)			RCP8.5 (quantiles)		
Massif	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %
Northern Alps																		
Chablais	1710	1920	2150	1600	1860	2030	1680	1930	2260	530	800	880	690	850	990	680	840	1050
Aravis	1580	1800	2400	1510	1720	1990	1580	1800	2140	750	750	750	750	750	920	750	750	980
Mont Blanc	1700	1900	2160	1510	1750	2030	1630	1830	2120	1050	1050	1050	1050	1050	1050	1050	1050	1050
Bauges	1720	1970	2180	1590	1860	2160	1580	1930	2250	450	710	940	450	750	1050	450	780	1050
Beaufortain	1620	1850	2330	1560	1750	2130	1630	1870	2280	750	750	750	750	750	770	750	750	930
Haute-Tarentaise	1780	2100	2490	1650	1850	2250	1730	2030	2420	750	750	750	750	750	750	750	750	750
Chartreuse	1870	2030	2250	1760	2020	2250	1840	2040	2250	770	880	1080	700	900	1150	720	930	1220
Belledonne	1660	1890	2120	1610	1840	2110	1690	1910	2260	610	720	950	640	780	1010	660	820	1080
Maurienne	1770	1990	2460	1640	1860	2160	1680	1930	2400	450	740	840	450	730	920	450	740	950
Vanoise	1740	2050	2490	1630	1840	2200	1740	1980	2400	750	750	750	750	750	750	750	750	750
Haute-Maurienne	2320	2470	2680	2200	2360	2670	2290	2460	2810	1050	1050	1050	1050	1050	1050	1050	1050	1050
Grandes-Rousses	1990	2220	2570	1910	2100	2540	1940	2210	2610	750	750	960	750	750	1010	750	750	1100
Vercors	1870	2030	2550	1910	2070	2400	1930	2140	2480	850	1020	1300	870	1030	1330	880	1080	1380
Oisans	1870	2180	2660	1940	2160	2560	2020	2280	2660	750	750	1020	750	750	1090	750	940	1200
Southern Alps																		
Thabor	2110	2410	2640	2050	2220	2580	2130	2440	2810	1350	1350	1350	1350	1350	1350	1350	1350	1350
Pelvoux	1990	2180	2900	1930	2190	2640	2050	2330	2820	1050	1050	1050	1050	1050	1050	1050	1050	1050
Queyras	2340	2620	3150	2320	2540	2900	2400	2690	3150	1050	1050	1050	1050	1050	1050	1050	1050	1050
Dévoluy	2010	2250	2660	2100	2330	2650	2190	2430	2810	920	1150	1390	1000	1200	1430	1020	1270	1460
Champsaur	2010	2260	2790	2030	2310	2660	2190	2420	2880	1050	1050	1050	1050	1050	1050	1050	1050	1050
Embrunnais Parpaillon	2240	2480	3090	2190	2500	2950	2320	2640	3060	750	750	1020	750	960	1100	750	980	1160
Ubaye	2360	2860	3150	2460	2770	3120	2590	2870	3150	1050	1050	1330	1050	1050	1410	1050	1050	1560
Haut-Var Haut-Verdon	2330	2620	2850	2300	2560	2850	2340	2650	2850	1140	1280	1500	1200	1350	1590	1200	1400	1690
Mercantour	2380	2640	3150	2350	2560	2880	2450	2680	3150	1250	1370	1560	1310	1430	1600	1330	1470	1690
French Pyrenees																		
Aspe Ossau	2000	2230	2480	2030	2280	2470	2070	2320	2590	1360	1500	1770	1380	1570	1870	1370	1570	2020
Haute-Bigorre	2070	2280	2690	2050	2230	2620	2080	2300	2820	1300	1480	1690	1220	1470	1710	1190	1460	1850
Aure Louron	2090	2340	2590	2050	2280	2590	2110	2370	2790	1260	1460	1700	1130	1350	1690	1140	1420	1870
Luchonnais	2070	2340	2590	2040	2270	2630	2080	2320	2660	1180	1400	1670	1140	1360	1700	1100	1380	1850
Couserans	1920	2120	2340	1830	2020	2330	1900	2100	2430	1120	1310	1520	1060	1220	1470	1110	1310	1600
Haute-Ariège	1960	2140	2380	1970	2080	2450	2010	2120	2560	1120	1300	1460	1070	1260	1470	1070	1270	1600
Orlu St-Barthélémy	2040	2280	2540	1950	2070	2540	2010	2200	2630	1280	1410	1630	1290	1430	1640	1280	1460	1750
Capcir-Puymorens	2640	2850	2850	2580	2760	2850	2640	2820	2850	1450	1650	1860	1440	1600	1770	1400	1620	2040
Cerdagne-Canigou	2610	2850	3150	2590	2860	3150	2640	2960	3150	1480	1630	1810	1450	1590	1800	1460	1650	1960
Spanish and Andorran Pyrenees																		
Andorra	2250	2550	2870	2140	2400	2820	2270	2580	3020	1290	1360	1540	1260	1390	1520	1290	1420	1720
Jacetiana	2280	2400	2600	2300	2380	2630	2320	2490	2850	1460	1680	1900	1550	1710	1920	1570	1760	1980
Gallego	2290	2410	2630	2310	2390	2650	2340	2600	3060	1450	1610	1800	1420	1630	1830	1460	1700	1980
Esera	2360	2620	2920	2360	2580	2830	2430	2660	3190	1310	1480	1700	1200	1450	1690	1320	1510	1930
Aran	2350	2660	3010	2340	2620	2960	2340	2610	3150	1260	1390	1700	1200	1370	1640	1230	1430	1830
Ribagorçana	2350	2590	2930	2380	2600	2870	2500	2670	3150	1350	1450	1770	1230	1420	1660	1300	1500	1880
Pallaresa	2350	2560	2870	2370	2590	2890	2450	2670	3140	1150	1320	1580	1140	1350	1580	1170	1430	1780
Ter-Freser	2370	2570	3000	2410	2690	3150	2510	2850	3150	1430	1530	1750	1410	1530	1740	1460	1570	1860
Cadi Moixero	2540	2850	2850	2600	2770	2850	2630	2850	2850	1350	1480	1750	1310	1490	1710	1380	1560	1920
Pre-Pyrenees	2250	2250	2250	2250	2250	2250	2250	2250	2250	1310	1460	1780	1340	1500	1780	1360	1580	1950

A3 End of the century (2080–2100)

Table A3. Snow reliability elevation for the end of the century (2080–2100) for the 42 massifs distributed over the northern Alps, southern Alps, French Pyrenees, and Spanish and Andorran Pyrenees, computed by climate models for the RCP2.6, RCP4.5 and RCP8.5 and for three reliability requirements (50 %, 70 % and 90 %).

	Groomed snow									Including snowmaking								
	RCP2.6 (quantiles)			RCP4.5 (quantiles)			RCP8.5 (quantiles)			RCP2.6 (quantiles)			RCP4.5 (quantiles)			RCP8.5 (quantiles)		
Massif	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %	50 %	70 %	90 %
Northern Alps																		
Chablais	1640	1880	2330	1820	2060	2560	2380	2640	2850	630	790	930	750	900	1090	1100	1350	1980
Aravis	1490	1780	2290	1700	1950	2480	2330	2610	2850	750	750	750	750	750	1030	1010	1200	1850
Mont Blanc	1570	1810	2390	1710	1950	2520	2310	2570	2900	1050	1050	1050	1050	1050	1050	1050	1050	1660
Bauges	1660	1980	2250	1780	2090	2250	2250	2250	2250	450	750	960	650	880	1240	1200	1640	2100
Beaufortain	1640	1820	2200	1730	1960	2600	2290	2570	3070	750	750	950	750	750	1000	1000	1130	1680
Haute-Tarentaise	1750	2160	2500	1820	2160	2820	2330	2670	3160	750	750	750	750	750	940	750	950	1140
Chartreuse	1830	2070	2250	2010	2250	2250	2250	2250	2250	700	950	1240	770	1060	1670	1790	1990	2220
Belledonne	1630	1800	2250	1800	2050	2560	2360	2610	3000	450	750	950	730	870	1190	1250	1620	2000
Maurienne	1780	1950	2370	1770	2090	2780	2330	2670	3120	450	690	980	680	810	1050	970	1170	1520
Vanoise	1720	2020	2470	1760	2140	2770	2320	2610	3080	750	750	750	750	750	750	750	1090	1440
Haute-Maurienne	2320	2500	2800	2360	2610	2930	2710	2970	3360	1050	1050	1050	1050	1050	1050	1050	1050	1500
Grandes-Rousses	1930	2210	2560	2010	2380	2810	2570	2850	3240	750	750	1000	750	750	1160	1120	1390	1830
Vercors	1830	2130	2550	2050	2310	2550	2550	2550	2550	920	1100	1300	980	1310	1660	1750	2020	2360
Oisans	1990	2160	2800	2090	2430	2900	2630	2890	3430	750	750	1000	750	1020	1290	1220	1580	1940
Southern Alps																		
Thabor	2150	2400	2720	2250	2570	2900	2790	2990	3150	1350	1350	1350	1350	1350	1350	1350	1350	1740
Pelvoux	2110	2340	2850	2140	2450	2900	2660	2960	3400	1050	1050	1050	1050	1050	1050	1050	1050	1410
Queyras	2460	2690	3150	2610	2900	3150	2980	3150	3150	1050	1050	1050	1050	1050	1050	1050	1240	1480
Dévoluy	2070	2330	2640	2330	2570	2880	2880	3060	3150	1050	1230	1380	1160	1320	1700	1730	2000	2330
Champsaur	2180	2440	2820	2330	2560	3020	2820	3120	3450	1050	1050	1050	1050	1050	1050	1050	1350	1710
Embrunnais Parpaillon	2430	2640	3060	2510	2820	3220	2970	3220	3450	750	750	1020	750	1060	1210	1300	1620	2130
Ubaye	2610	2890	3150	2760	2970	3150	3030	3150	3150	1050	1050	1300	1050	1250	1660	1560	1880	2320
Haut-Var Haut-Verdon	2330	2560	2850	2540	2780	2850	2850	2850	2850	1160	1330	1560	1300	1540	1850	1900	2090	2410
Mercantour	2300	2570	2880	2590	2820	3150	3020	3150	3150	1270	1340	1510	1370	1500	1760	1750	1990	2480
French Pyrenees																		
Aspe Ossau	2000	2190	2540	2260	2400	2650	2780	2940	3150	1350	1470	1840	1480	1750	2130	2180	2380	2840
Haute-Bigorre	2000	2180	2480	2250	2380	2980	2990	3200	3450	1290	1470	1610	1400	1620	1890	1990	2220	3060
Aure Louron	2030	2190	2650	2310	2490	2880	2900	3150	3150	1130	1300	1720	1340	1670	1960	1980	2180	2720
Luchonnais	2000	2220	2740	2280	2550	2860	2900	3150	3450	1160	1360	1750	1330	1600	1950	1990	2180	2680
Couserans	1840	2030	2350	2030	2260	2480	2600	2830	3150	1060	1230	1490	1250	1400	1700	1830	2020	2560
Haute-Ariège	1910	2050	2410	2060	2330	2790	2770	3010	3150	1050	1220	1480	1180	1410	1690	1760	2020	2590
Orlu St-Barthélémy	1910	2140	2370	2100	2440	2840	2690	2850	2850	1260	1410	1630	1380	1570	1850	1900	2140	2680
Capcir Puymorens	2510	2690	2850	2710	2850	2850	2850	2850	2850	1430	1540	1800	1530	1740	2110	2170	2370	2770
Cerdagne Canigou	2450	2640	3150	2770	3060	3150	3150	3150	3150	1470	1620	1830	1550	1730	2020	2010	2270	2750
Spanish and Andorran Pyrenees																		
Andorra	2090	2240	2560	2360	2750	3150	3010	3150	3150	1230	1350	1600	1350	1490	1810	1870	2070	2640
Jacetiana	2280	2410	2700	2360	2570	2810	2950	3150	3150	1470	1680	1910	1690	1870	2060	2190	2370	2810
Gallego	2350	2510	2750	2390	2640	2990	3040	3150	3150	1390	1500	1730	1590	1780	2030	2140	2390	2880
Esera	2440	2610	2950	2570	2790	3080	3060	3260	3450	1300	1500	1640	1460	1670	1940	2050	2230	2720
Aran	2260	2520	2780	2570	2850	3150	3120	3150	3150	1120	1340	1620	1340	1550	1970	1940	2160	2720
Ribagorçana	2350	2680	2950	2590	2820	3150	3040	3150	3150	1300	1500	1710	1460	1650	1910	2040	2250	2690
Pallaresa	2350	2620	3020	2630	2840	3150	3130	3150	3150	1170	1340	1710	1390	1570	1880	2010	2200	2710
Ter-Freser	2320	2600	3040	2670	2920	3150	3150	3150	3150	1370	1480	1730	1510	1670	1950	2020	2280	2740
Cadi Moixero	2500	2850	2850	2730	2850	2850	2850	2850	2850	1350	1550	1800	1480	1690	2010	1990	2290	2850
Pre-Pyrenees	2250	2250	2250	2250	2250	2250	2250	2250	2250	1210	1500	1800	1470	1710	1970	1970	2210	2250

Appendix B: Detailed features of individual ski resorts

Table B1. Main features of the 175 ski resorts included in the present work grouped by massifs and major areas (northern and southern Alps, French and Spanish and Andorran Pyrenees).

	Resort features				
	Ski lift power	Size category	Village elevation	Mean elevation	Max. elevation
Chablais (northern Alps)					
Lullin-Col du Feu	81	S	1084	1130	1175
Plaine-Joux	749	S	1372	1508	1718
Abondance	1205	S	1049	1341	1758
Habère-Poche	1454	S	1018	1200	1505
Bellevaux Hirmentaz	2115	S	1185	1331	1612
Bernex	2372	S	1009	1396	1871
Thollon Les Mémises	2468	S	1048	1518	1938
Brasses (Les)	2617	M	1148	1249	1495
Espace Roc d'Enfer	3100	M	1013	1351	1790
Chapelle d'Abondance (la)	3156	M	1054	1410	1797
Praz-de-Lys – Sommand	5099	L	1453	1487	1961
Carroz d'Arâches (Les)	7348	L	1160	1561	2109
Morzine Pleney Nyon	9204	L	1012	1467	2127
Gets (Les)	10 489	L	1202	1502	2131
Morillon–Samoëns–Sixt	12 159	L	968	1501	2118
Grand Massif (Flaine – Vallée du Giffre)	13 466	L	1662	1982	2482
Châtel	13 959	L	1208	1631	2093
Avoriaz – Morzine	18 826	XL	1758	1815	2501
Aravis (northern Alps)					
Cret (Saint-Jean-de-Sixt)	49	S	959	843	1020
Montmin	96	S	1152	1101	1195
Reposoir (Le)	271	S	1039	1301	1626
Rafforts (Les) – Ugine	285	S	939	1067	1225
Nancy-sur-Cluses	354	S	1291	1341	1558
Mont-Saxonnex	828	S	1059	1346	1574
Portes du Mont-Blanc (Les) – Sallanches-Cordon	1005	S	1106	1315	1538
Manigod Croix Fry	2088	S	1502	1491	1795
Portes du Mont-Blanc (Les) – Combloux – Le Jaillet – La Giettaz	4753	M	1152	1405	1982
Grand Bornand (Le)	11 400	L	1254	1509	2031
Clusaz (La)	13 826	L	1126	1612	2375
Mont Blanc (northern Alps)					
Vallorcine La Poya	1503	S	1358	1577	1932
Saint-Nicolas-de-Véroce	3657	M	1241	1751	2364
Les Houches – Saint-Gervais	5872	L	1068	1532	1892
Saint-Gervais Bettex	7293	L	1084	1549	2386
Contamines (Les)-Hauteluce	10 409	L	1206	1786	2437
Megève	15 132	XL	1175	1557	2014
Chamonix	27 378	XL	1160	1938	3787
Bauges (northern Alps)					
Seythenex – La Sambuy	1170	S	1160	1429	1835
Savoie Grand Revard	1287	S	1376	1339	1549
Semnoz (Le)	1474	S	1480	1505	1696
Aillon-le-Jeune-Margériaz	3594	M	1029	1430	1834

Table B1. Continued.

	Resort features				
	Ski lift power	Size category	Village elevation	Mean elevation	Max. elevation
Beaufortain (northern Alps)					
Granier-sur-Aime	224	S	1394	1522	1661
Crest-Voland	3472	M	1257	1410	1608
Arêches-Beaufort	4247	M	1104	1573	2137
Val d'Arly	8345	L	1158	1498	2053
Saisies (Les)	8433	L	1529	1727	2052
Haute-Tarentaise (northern Alps)					
Sainte-Foy-Tarentaise	2436	S	1536	2067	2612
Rosière (la)	6969	L	1841	2031	2572
Val d'Isère	24 371	XL	1868	2368	3197
Tignes	25 814	XL	2092	2251	3459
Arcs (Les) – Peisey-Vallandry	31 699	XL	1786	1826	3220
Chartreuse (northern Alps)					
Col de Marcieu	221	S	1070	1184	1350
Sappey-en-Chartreuse (Le)	362	S	988	1104	1344
Col de Porte	372	S	1329	1370	1615
Col du Granier – Désert d'Entremont (Le)	506	S	1106	1207	1428
Saint-Hilaire-du-Touvet	517	S	974	1075	1415
Saint-Pierre-de-Chartreuse – Le Planolet	2958	M	982	1318	1751
Belledonne (northern Alps)					
Col du Barioz Alpin	190	S	1366	1505	1684
Collet d'Allevard (Le)	2897	M	1452	1715	2091
Chamrousse	7078	L	1732	1880	2253
Sept Laux (Les)	10 881	L	1396	1786	2378
Maurienne (northern Alps)					
Saint-Colomban-des-Villards	1732	S	1117	1586	2234
Albiez Montrond	2708	M	1570	1725	2060
Karellis (Les)	4986	M	1608	2043	2490
Toussuire (La) – Saint-Pancrace (Les Bottieres)	6148	L	1667	1939	2367
Corbier (Le)-Saint-Jean-d'Arves	6363	L	1555	1791	2377
Valmeinier	7718	L	1719	2017	2579
Valloire	9631	L	1482	1597	2530
Vanoise (northern Alps)					
Notre-Dame-du-Pré	226	S	1279	1365	1510
Aussois	3055	M	1535	2096	2670
Pralognan	3505	M	1438	1495	2340
Orelle	5217	L	2364	2003	3242
Saint-François-Longchamp	6405	L	1583	1904	2514
Valmorel	11 005	L	1382	1748	2401
Meribel Les Allues	15 767	XL	1362	1913	2701
Val Thorens	19 844	XL	2300	2501	3186
Menuires (Les)	22 331	XL	1798	2185	2845
Plagne (La)	35 044	XL	1849	2028	3167
Courchevel	39 787	XL	1667	2084	2919

Table B1. Continued.

	Resort features				
	Ski lift power	Size category	Village elevation	Mean elevation	Max. elevation
Haute-Maurienne (northern Alps)					
Bramans	16	S	1261	1277	1315
Bessans	185	S	1715	1849	2079
Bonneval sur Arc	2024	S	1831	2339	2937
Valfréjus	3773	M	1627	2086	2731
Norma (La)	4032	M	1387	1964	2742
Val Cenis	13 212	L	1440	1921	2737
Grandes-Rousses (northern Alps)					
Chazelet-Villar d'Arene	1088	S	1664	1898	2164
Saint Sorlin d'Arves	7746	L	1556	2028	2590
Oz – Vaujany	8072	L	1311	1853	2817
Alpe d'Huez (l')	18 232	XL	1771	2125	3318
Vercors (northern Alps)					
Saint-Nizier	22	S	1176	1181	1200
Rencurel	221	S	1081	1137	1233
Col de l'Arzelier	472	S	1171	1311	1477
Font d'Urle – Chaud Clapier	504	S	1433	1405	1542
Gresse-en-Vercors	1257	S	1251	1396	1703
Col de Rousset	1297	S	1275	1424	1695
Autrans	1535	S	1074	1415	1650
Méaudre	1645	S	1009	1265	1577
Lans en Vercors	1880	S	1137	1523	1801
Villard-de-Lans-Corrençon	9644	L	1221	1575	2052
Oisans (northern Alps)					
Notre-Dame-de-Vaulx	18	S	972	1058	1085
Villard Reymond	37	S	1650	1691	1712
Motte d'Aveillans (La)	84	S	1285	1360	1430
Saint-Firmin-Valgaudemar	91	S	1306	1470	1580
Col d'Ornon	401	S	1366	1559	1855
Grave (La)	995	S	1498	2479	3532
Alpe du Grand Serre (l')	3225	M	1403	1716	2221
Deux Alpes (Les)	23 796	XL	1720	2344	3642
Thabor (southern Alps)					
Névache	112	S	1609	1643	1707
Montgenèvre	8587	L	1845	2143	2581
Pelvoux (southern Alps)					
Pelvoux-Vallouise	1391	S	1398	1615	2237
Puy-Saint-Vincent	5734	L	1645	1938	2668
Serre Chevalier	26 571	XL	1376	1993	2750
Queyras (southern Alps)					
Stations du Queyras	6834	L	1819	2024	2801
Dévoluy (southern Alps)					
Lus la Jarjatte	385	S	1171	1339	1521
Massif du Dévoluy	7068	L	1506	1591	2490

Table B1. Continued.

	Resort features				
	Ski lift power	Size category	Village elevation	Mean elevation	Max. elevation
Champsaur (southern Alps)					
Ancelle	1842	S	1351	1511	1811
Stations Village du Champsaur	3907	M	1386	1486	2240
Orcières Merlette	8297	L	1836	2178	2725
Embrunnais Parpaillon (southern Alps)					
Réallon	1408	S	1569	1789	2114
Orres (Les)	6545	L	1687	2027	2704
Risoul	6734	L	1900	2188	2551
Ubaye (southern Alps)					
Col Saint Jean	2952	M	1345	1883	2450
Stations de l'Ubaye	5825	L	1523	1909	2427
Pra Loup	6772	L	1621	1904	2500
Vars	9073	L	1832	2079	2721
Haut-Var Haut-Verdon (southern Alps)					
Val Pelens	169	S	1612	1662	1737
Roubion les Buisses	728	S	1443	1611	1898
Valberg-Beuil	4849	M	1665	1650	2020
Val d'Allos	8257	L	1730	1580	2500
Mercantour (southern Alps)					
Stations du Mercantour	17 669	XL	1784	2029	2585
Aspe Ossau (French Pyrenees)					
Artouste	2565	M	1894	1730	2040
Gourette – Pierre Saint Martin (La)	8788	L	1420	1543	2453
Haute-Bigorre (French Pyrenees)					
Val d'Azun	14	S	1469	1469	1469
Pic du Midi	516	S	1780	2292	2856
Hautacam	919	S	1520	1454	1729
Gavarnie	1999	S	1846	1997	2282
Piau Engaly	3819	M	1841	2030	2529
Luz Ardiden	4099	M	1716	1951	2484
Cauterets	7193	L	1755	1932	2416
Tourmalet	10 243	L	1784	1866	2490
Saint Lary Soulan	12 822	L	1653	1991	2471
Aure Louron (French Pyrenees)					
Val Louron	1693	S	1462	1723	2058
Peyragudes	7741	L	1623	1884	2260
Luchonnais (French Pyrenees)					
Bourg d'Oueil	109	S	1345	1438	1498
Superbagnères	6446	L	1792	1736	2133
Couserans (French Pyrenees)					
Le Mourtis	1096	S	1425	1578	1801
Guzet Neige	2673	M	1445	1600	2050
Haute-Ariege (French Pyrenees)					
Ax Les Thermes	7437	L	1398	1955	2948

Table B1. Continued.

	Resort features				
	Ski lift power	Size category	Village elevation	Mean elevation	Max. elevation
Orlu St-Barthélémy (French Pyrenees)					
Camurac	527	S	1417	1335	1755
Ascou	820	S	1558	1731	2058
Mijane – Goulier – Plateau de Beille	891	S	1663	1599	2013
Monts d'Olmes	1922	S	1487	1647	1948
Capcir Puymorens (French Pyrenees)					
Quillane (La)	111	S	1709	1752	1812
Porté-Puymorens	1800	S	1755	1259	2342
Formiguères	1869	S	1769	1974	2320
Font Romeu – P2000	5132	L	1775	1982	2227
Angles (Les)	5478	L	1683	1968	2361
Cerdagne Canigou (French Pyrenees)					
Cambre d'Aze	1741	S	1745	1958	2424
Andorra (Spanish and Andorran Pyrenees)					
Arinsal	1663	S	1706	2147	2531
Pal	3054	M	1651	2062	2351
Ordino-Arcalis	3897	M	1792	2281	2633
Grandvalira	19 747	XL	1772	2251	2669
Jacetania (Spanish and Andorran Pyrenees)					
Astún	3304	M	1591	1968	2249
Candanchú	4573	M	1506	1836	2283
Formigal	11 251	L	1562	1923	2263
Gallego (Spanish and Andorran Pyrenees)					
Panticosa	2799	M	1476	1789	2191
Esera (Spanish and Andorran Pyrenees)					
Cerler	7000	L	1694	2129	2645
Aran (Spanish and Andorran Pyrenees)					
Baqueira Beret	21 246	XL	1685	2115	2543
Ribagorçana (Spanish and Andorran Pyrenees)					
Boí Taüll	4648	M	1825	2333	2741
Pallaresa (Spanish and Andorran Pyrenees)					
Espot	2554	M	1609	1997	2339
Port Ainé	2927	M	1714	2160	2432
Tavascan	774	S	1582	1954	2220
Ter-Freser (Spanish and Andorran Pyrenees)					
Vall de Núria	1040	S	1656	2070	2303
Vallter 2000	2036	S	1797	2289	2526
Cadi Moixero (Spanish and Andorran Pyrenees)					
La Molina	14 282	L	1603	1988	2527
Pre-Pyrenees (Spanish and Andorran Pyrenees)					
Port del Comte	5301	L	1624	2020	2329

Author contributions. SM and EG designed the research; PS developed the model, carried out the experiments, and produced the data and most figures with support from co-authors; HF contributed to produce the data and mapping figures; DV produced the adjusted climate projections; ML contributed to the development of the model and production of climate forcing data; MV contributed to the production of the reanalysis forcing data; MP provided input for the Spanish and Andorran resorts; all authors contributed to the analysis and interpretation of the results; PS wrote the paper, based on input and feedback from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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