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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. 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 on-going climate change. The technical reliability (i.e. including snowmaking) is projected to rise by 200 m to 300 m in the Alps and by 400 m 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 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 of 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 French Alps and Pyrenees (France, Spain and Andorra) at the end of the century (2080 - 2100). Only 24 resorts are projected to remain technically reliable, all being located in the Alps.

1 Introduction

The on-going evolution of natural snow conditions related to climate change (Beniston et al., 2018) is increasingly regarded as a major threat for the winter tourism (Gilaberte-Burdalo et al., 2014; Steiger et al., 2017; Hoegh-Guldberg et al., accepted). This prompts the question of how climate change affects ski resorts and the relevance of snowmaking as adaptation measure (Steiger et al., 2017). Initial studies in the early 2000’s 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 et al., 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 days or more, which provides objective
information when comparing distinct periods (past and future) or locations (Koenig and Abegg, 1997; Elsasser et al., 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 et al., 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 slopes surface area was concentrated. These remain coarse representations limiting the analysis of the situation of a ski resort to a binary conclusion reliable/unreliable (Steiger et al., 2017). Koenig and Abegg (1997) and Elsasser et al. (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 of 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% 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°C warming compared to present, only 75% of European Alps ski resorts would remain reliable and respectively 61% and 30% for +2°C and +4°C warming compared to present. 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 snow making (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 Québec 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 of water and energy requirements (Steiger, 2010). Similar investigations were conducted to assess the
The impact of climate change on the ski season duration and the snowmaking requirements so as to compensate 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), Pyrenees (Pons et al., 2015; Gilaberte-Búrdalo et al., 2017), Northeast U.S.A (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, yet 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 resorts 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 lifts 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 km) and its capacity, i.e. the flow of persons per hour (pers h⁻¹), expressed in pers km h⁻¹. Ski lift infrastructures in France have a total ski lift power of 977’000 pers km h⁻¹, 94% of which are included in the present study (Appendix B). These data are completed with geographical information from the database.
BDTOPO (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 lifts elevation is defined as the average of top and bottom elevations of each ski lift weighted by its ski lift power, being simply 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 buildings (taking account the number of floors, based on building height), which is used to compute the weighted mean elevation of the built area associated to each resort, weighted by their net floor area (Breiling and Charamza, 1999).

Data for computing the mean ski lifts 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/), we estimated the main features for the Spanish and Andorran ski resorts (village elevation, ski lift mean elevation and ski lift power). However, ski lifts capacity is not included in OSM, and building height data is 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 (Figure 1).

- The linear model of the ski lift power versus the OSM surface area (Figure 1 left) 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 (Figure 1 right):
  - All elevations together: RMSD = 149 m, mean difference = 15 m.
    Linear model of slope 0.97 ($R^2 = 0.91$, p-value < $10^{-15}$).
  - Mean elevation: RMSD = 154 m, mean difference = 51 m.
    Linear model of slope 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 < $10^{-12}$ (Figure 1 right).
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 (Figure 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 Molina and Masella were considered together). In terms of skiers, the Spanish Pyrenees represent around 63% of the total ski Market in Spain.

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 taking 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 $1.2 \times 10^{-3}$ 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 November 1 and December 15, 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 December 15 and February 28, snow is produced, if meteorologically possible, so as to maintain a total snow depth of 60 cm.

- After March 1, 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 “massif”, covering French Alps and Pyrenees, including Spanish and Andorran Pyrenees (Figure 2). Within each massif, the meteorological conditions are supposed 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; Maris et al., 2009; Durand et al., 2012). 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 days between December 15 and April 15 (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 massifs elevations (300 m step), a linear interpolation was used to compute the snow reliability line meeting the 100 days threshold. In cases where the season length at the minimum (respectively maximum) elevation was longer (respectively shorter) than 100 days, 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 scenarios 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 days one season out of two (50% percentile of annual values), seven seasons out of ten (70% percentile of annual values) and nine seasons out of ten (90% percentile of annual values). Last, we considered the groomed snow conditions (no snowmaking) and including snowmaking (two configurations). We do not compute indicators based on natural snow conditions alone, i.e. without grooming and snowmaking.
| RCM (institute)/GCM | Period | CNRM-CM5 | EC-EARTH | HadGEM2-ES | MPI-ESM-LR | IPSL-CM5A-MR |
|---------------------|--------|----------|-----------|-------------|-------------|--------------|
| CCLM 4.8.17 (CLMcom) |        | 1950-2005 | 1950-2005 | 1981-2005 | 1950-2005 |               |
|                     |        | 2006-2100 | 2006-2100 | 2006-2099 | 2006-2100 |               |
| ALADIN 53 (CNRM)    | HIST   | 1950-2005 |           |             |             |               |
|                     | RCPs   |          |           |             |             |               |
|                     |        | 2006-2100 |           |             |             |               |
| WRF 3.3.1F (IPSL-INERIS) | HIST |           |           |             |             |               |
|                     | RCPs   |           |           |             |             |               |
|                     |        |           |           |             |             | 1951-2005     |
|                     |        |           |           |             |             | 2006-2100     |
| RACMO 2.2E (KNMI)   | HIST   |           |           |             |             |               |
|                     | RCPs   |           |           |             |             |               |
|                     |        |           |           |             |             | 2006-2099     |
| REMO 2009 (MPI-CSC) | HIST   |           |           |             |             |               |
|                     | RCPs   |           |           |             |             |               |
|                     |        |           |           |             |             | 1950-2005     |
|                     |        |           |           |             |             | 2006-2100     |
| RCA 4 (SMHI)        | HIST   | 1970-2005 | 1970-2005 | 1981-2005 | 1970-2005 | 1970-2005     |
|                     | RCPs   | 2006-2100 | 2006-2100 | 2006-2100 | 2006-2100 | 2006-2100     |

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 8.5 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, Norrkoping Sweden

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 ten 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 infrastructure. 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, starting 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% snow-making reliability line
- Category 3: mean ski lifts elevation above the 70% groomed snow reliability line and village elevation above the 90% snowmaking reliability line
- Category 4: mean ski lifts 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 lifts elevation above the 90% snowmaking reliability line
- Category 7: mean ski lifts 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 may not be considered as reliable and snowmaking is no longer 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 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, Figure 3). Although a deviation can be observed, the spatial variability is consistent between climate models 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 (Figure 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 technical reliability line significantly lower in the Southern Alps compared to the Pyrenees despite poorer natural snow conditions (Figure 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 (Figure 3). The median 70% groomed snow reliability line is projected to range between:

- 1850 m.a.s.l and 2000 m.a.s.l in the Northern Alps
  (100 to 250 m above the reference period)
- 2500 m.a.s.l and 2650 m.a.s.l in the Southern Alps
  (200 to 400 m above the reference period)
- 2250 m.a.s.l and 2300 m.a.s.l in the French Pyrenees
  (300 to 350 m above the reference period)
- 2550 m.a.s.l 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 m to 300 m in the Northern Alps, 300 m in the Southern Alps and up to 400 m to 600 m in the Pyrenees compared to the reference period. In the near future the median elevation of the technical reliability is projected to range between 950 m.a.s.l to 1050 m.a.s.l in the Northern Alps, 1350 m.a.s.l in the Southern Alps, 1700 m.a.s.l to 1850 m.a.s.l in the French Pyrenees, 1750 m.a.s.l 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 technical reliability between these areas (Figure 3).
3.1.3 Future change at the end of the century (2080-2100)

The impact of climate change on the 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, the median 70% groomed snow reliability line ranging between 200 m to 300 m above the elevation for the reference period. According to the 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, up to 1050 m in the French Pyrenees.

The technical 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 the RCP2.6 and up to 1100 m (Northern and Southern Alps) to 1450 m (French Pyrenees) higher for the RCP8.5. The median elevation of the technical reliability for the 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 (Figure 3).

5 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%.

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

Table 2. Distribution of the total ski lift power (%) within reliability categories for distinct periods and scenarios (Figure 4) with the number of resorts included (n).
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), either with natural snow conditions (50% in categories 1, 2 and 3 altogether, Table 2, HIST) or technically (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 natural snow reliable and 129 ski resorts also representing 49% of the ski lift power being only technically reliable (Table 2). Categories 6 and 7 include resorts where 90% technical reliability can not be achieved at the elevation of the village (category 6) or at the mean ski lifts elevation (category 7). These categories represent the situation of a marginal fraction of ski resorts in the reference period: less than 1% unreliable facilities (2 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 natural 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 (Figure 3, Appendix A1) and the higher elevation of larger ski resorts, most of them being located in the Northern Alps and central Pyrenees (Figures 2 and 5). The variability is particularly high between Northern Alps (a majority of ski resorts were natural snow reliable: 67% of ski lift power) and the Southern Alps (89% were technically reliable) highlighting a higher dependence of Southern Alps ski resorts to snowmaking in the reference period (only 12% of ski lift power were natural snow reliable). The situation of the Pyrenees ski resorts lies in-between (Figure 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 central Pyrenees (Table 2). An additional 83 to 116 resorts (representing 49 to 64% of ski lift power) are projected to remain technically reliable thanks to snowmaking. Overall, a majority of ski resorts would remain reliable, either technically 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 in category 7 (2 to 7% of ski lift power) where 90% technical reliability can not be achieved at the elevation of the village (category 6) or at the mean ski lifts 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 natural snow reliable ski resort in the Southern Alps, snow conditions are projected to remain technically reliable for most resorts (reduction from 100% to 89% of technically reliable ski lift power), displaying a consistent distribution between reliability categories compared to the reference period (Figure 4). On the contrary, the projected impact on the Pyrenees ski resorts is significant, particularly in the French Pyrenees. There would remain a single resort being natural snow reliable 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 on the availability of suitable periods for snowmaking (Figure 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 resorts reliability for the 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 the RCP8.5 with only 24 ski resorts (28% of ski lift power) benefiting from technical reliability (Table 2), all of them being located in the Alps. Figure 4 illustrate 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 technically reliable ski resorts 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.

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 approximate 1000 km² 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 (Figures 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 points representations are considered on 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 a 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 as an efficient method to technically reduce the impacts of natural snow scarcity, the attractiveness of
Figure 5. Fraction of ski lift power (%) for a given category (Section 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 technically reliable. 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.

A given resort may be damaged either due to the lack of snow in parts of the ski resort not equipped with facilities or even due the lack of natural snow (landscapes, winter spirit).

We provided information beyond a binary assessment reliable/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 other dimensions 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 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 either for the reference period (1986-2005) and under future climate conditions. Snowmaking appears as an efficient method to improve the snow reliability with 99% of ski lift facilities technically reliable for the reference period. This is particularly true in the Southern Alps where snowmaking leads to lower elevation of the technical 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 of natural snow conditions and of 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 technical 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 cm to 140 cm 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 of the snow reliability (RCP8.5). At the end of the century and for the 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) benefiting from technical 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 a 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 ongoing 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-21$^{st}$ century snowmaking appears to be an efficient adaptation option to reduce the climate change hazard to ski resorts 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 analyze and assess all dimensions of climate change impacts and risk to this key mountain economic sector, in France and many other places on Earth.

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; 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 there is no conflict of interest regarding the publication of this article.

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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%).

| Massif               | Groomed snow | Including snowmaking |
|----------------------|--------------|----------------------|
|                      | SAFRAN       | HIST                 | SAFRAN       | HIST       |
|                      | (Quantiles)  | (Quantiles)          | (Quantiles)  | (Quantiles) |
|                      | 50%   70%  90% | 50%   70%  90%       | 50%   70%  90% | 50%   70%  90% |
| **Northern Alps**    |              |                      |              |              |
| Chablais             | 1240 1410 1630 | 1250 1380 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 |
| Devoluy              | 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 |
| Embrunnaiss Parpaillon | 2110 2520 2960 | 2040 2260 2810       | 750 940 1170  | 750 750 960  |
|          | Ubaye | Haut-Var | Haut-Verdon | Mercantour |
|----------|-------|----------|-------------|------------|
|          | 2250  | 2140     | 2210        | 2050       |
|          | 2560  | 2330     | 2360        | 2360       |
|          | 2940  | 2580     | 2760        | 2760       |
|          | 2300  | 2060     | 2100        | 2100       |
|          | 2530  | 2280     | 2330        | 2330       |
|          | 2910  | 2690     | 2740        | 2740       |
|          | 1050  | 960      | 1050        | 1050       |
|          | 1050  | 1230     | 1280        | 1280       |
|          | 1230  | 1350     | 1360        | 1390       |
|          | 1050  | 900      | 1050        | 1050       |
|          | 1050  | 1080     | 1240        | 1390       |
|          | 1050  | 1300     |             |            |

### French Pyrenees

|          | Aspe Ossau | Haute-Bigorre | Aure Louron | Luchonnais | Couserans | Haute-Ariege | Orlu St-Barthelemy | Capcir Puymorens | Cerdagne Canigou |
|----------|------------|---------------|-------------|------------|-----------|--------------|---------------------|------------------|-----------------|
|          | 1480       | 1670          | 1630        | 1650       | 1430      | 1490         | 1580                | 2050             | 2180            |
|          | 1620       | 1730          | 1860        | 1830       | 1620      | 1640         | 1680                | 2380             | 2360            |
|          | 1930       | 1950          | 1940        | 2020       | 1770      | 1770         | 1800                | 2580             | 2580            |
|          | 1970       | 1980          | 2010        | 2020       | 1740      | 1740         | 1880                | 2690             | 2580            |
|          | 2210       | 2220          | 2270        | 2280       | 2050      | 2240         | 2240                | 3200             | 2780            |
|          | 960        | 970           | 930         | 890        | 900       | 890          | 1050                | 1200             | 1180            |
|          | 1050       | 1060          | 990         | 960        | 1000      | 970          | 1230                | 1310             | 1180            |
|          | 1400       | 1380          | 1310        | 1420       | 1180      | 1240         | 1310                | 1540             | 1600            |
|          | 1080       | 910           | 850         | 750        | 800       | 800          | 1230                | 1260             | 1210            |
|          | 1220       | 1080          | 980         | 900        | 930       | 940          | 1230                | 1260             | 1130            |
|          | 1400       | 1260          | 1180        | 1180       | 1130      | 1130         | 1310                | 1330             | 1150            |

### Spanish and Andorran Pyrenees

|          | Andorra | Jacetiana | Gallego | Esera | Aran | Ribagorcan | Pallaresa | Ter-Freser | Cadi Moixero | Pre-Pirineu |
|----------|---------|-----------|---------|-------|------|------------|-----------|------------|--------------|-------------|
|          | 1790    | 1860      | 1780    | 2050  | 1950 | 1960       | 1900      | 2060       | 2010        | 1960        |
|          | 1990    | 1930      | 1900    | 2260  | 2070 | 2200       | 2150      | 2570       | 2070        | 2060        |
|          | 2370    | 2010      | 2040    | 2360  | 2200 | 2350       | 2450      | 2810       | 2450        | 2250        |
|          | 1930    | 2010      | 2110    | 2150  | 2080 | 2200       | 2040      | 2060       | 2010        | 2060        |
|          | 2100    | 2140      | 2300    | 2290  | 2330 | 2350       | 2260      | 2350       | 2070        | 2250        |
|          | 2530    | 2340      | 2650    | 2560  | 2630 | 2780       | 2640      | 2780       | 2530        | 2250        |
|          | 2950    | 1180      | 1110    | 1040  | 1020 | 1070       | 930       | 1250       | 1060        | 1020        |
|          | 1290    | 1280      | 1160    | 1170  | 1140 | 1150       | 1050      | 1320       | 1170        | 1230        |
|          | 860     | 1170      | 1110    | 1050  | 1020 | 1070       | 890       | 1250       | 1180        | 1180        |
|          | 1080    | 1350      | 1110    | 1170  | 1140 | 1130       | 900       | 1320       | 1180        | 1180        |
|          | 1290    | 1470      | 1240    | 1290  | 1140 | 1130       | 750       | 1300       | 1180        | 1420        |

|          | 1290    | 1530      | 1470    | 1340  | 1460 | 1340       | 1200      | 1440       | 1380        | 1420        |

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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 distinct reliability requirements (50%, 70% and 90%).

| Massif          | Groomed Snow | Including Snowmaking |
|-----------------|--------------|----------------------|
|                 | RCP2.6       | RCP4.5               | RCP8.5               | RCP2.6 | RCP4.5 | RCP8.5 |
|                 | (Quantiles)  | (Quantiles)          | (Quantiles)          | (Quantiles) | (Quantiles) | (Quantiles) |
|                 | 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 |
| Devoluy         | 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 |

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| Region                | 2000 | 2230 | 2480 | 2030 | 2280 | 2470 | 2070 | 2320 | 2590 | 1360 | 1500 | 1770 | 1380 | 1570 | 1870 | 1370 | 1570 | 2020 |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 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-Ariege          | 1960 | 2140 | 2380 | 1970 | 2080 | 2450 | 2010 | 2120 | 2560 | 1120 | 1300 | 1460 | 1070 | 1260 | 1470 | 1070 | 1270 | 1600 |
| Orlu St-Barthelemy    | 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 |
| Ribagorcana           | 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-Pirineu           | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 1310 | 1460 | 1780 | 1340 | 1500 | 1780 | 1360 | 1580 | 1950 |
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 distinct reliability requirements (50%, 70% and 90%).

| Massif                | Groomed Snow (Quantiles) | Including Snowmaking (Quantiles) |
|-----------------------|---------------------------|----------------------------------|
|                       | RCP2.6 | RCP4.5 | RCP8.5 | RCP2.6 | RCP4.5 | RCP8.5 |
|                       | 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    |
| Aravis                | 1490   | 1780   | 2290   | 1700   | 1950   | 2480   | 2330   | 2610   | 2850   | 750    | 750    | 750    |
| Mont-Blanc            | 1570   | 1810   | 2390   | 1710   | 1950   | 2520   | 2310   | 2570   | 2900   | 1050   | 1050   | 1050   |
| Bauges                | 1660   | 1980   | 2250   | 1780   | 2090   | 2250   | 2250   | 2250   | 2250   | 450    | 750    | 960    |
| Beaufortain           | 1640   | 1820   | 2200   | 1730   | 1960   | 2600   | 2290   | 2570   | 3070   | 750    | 750    | 950    |
| Haute-Tarentaise      | 1750   | 2160   | 2500   | 1820   | 2160   | 2820   | 2330   | 2670   | 3160   | 750    | 750    | 940    |
| Chartreuse            | 1830   | 2070   | 2250   | 2010   | 2250   | 2250   | 2250   | 2250   | 2250   | 700    | 950    | 1240   |
| Belledonne            | 1630   | 1800   | 2250   | 1800   | 2050   | 2560   | 2360   | 2610   | 3000   | 450    | 750    | 950    |
| Maurienne             | 1780   | 1950   | 2370   | 1770   | 2090   | 2780   | 2330   | 2670   | 3120   | 450    | 690    | 980    |
| Vanoise               | 1720   | 2020   | 2470   | 1760   | 2140   | 2770   | 2320   | 2610   | 3080   | 750    | 750    | 750    |
| Haute-Maurienne       | 2320   | 2500   | 2800   | 2360   | 2610   | 2930   | 2710   | 2970   | 3360   | 1050   | 1050   | 1050   |
| Grandes-Rousses       | 1930   | 2210   | 2560   | 2010   | 2380   | 2810   | 2570   | 2850   | 3240   | 750    | 750    | 1000   |
| Vercors               | 1830   | 2130   | 2550   | 2050   | 2310   | 2550   | 2550   | 2550   | 2550   | 920    | 1100   | 1300   |
| Oisans                | 1990   | 2160   | 2800   | 2090   | 2430   | 2900   | 2630   | 2890   | 3430   | 750    | 750    | 1000   |
| **Southern Alps**     |        |        |        |        |        |        |        |        |        |        |        |        |
| Thabor                | 2150   | 2400   | 2720   | 2250   | 2570   | 2900   | 2790   | 2990   | 3150   | 1350   | 1350   | 1350   |
| Pelvoux               | 2110   | 2340   | 2850   | 2140   | 2450   | 2900   | 2660   | 2960   | 3400   | 1050   | 1050   | 1050   |
| Queyras               | 2460   | 2690   | 3150   | 2610   | 2900   | 3150   | 2980   | 3150   | 3150   | 1050   | 1050   | 1050   |
| Devoluy               | 2070   | 2330   | 2640   | 2330   | 2570   | 2880   | 2880   | 3060   | 3150   | 1050   | 1230   | 1380   |
| Champsaur             | 2180   | 2440   | 2820   | 2330   | 2560   | 3020   | 2820   | 3120   | 3450   | 1050   | 1050   | 1050   |
| Embrunnais Parpaillon | 2430   | 2640   | 3060   | 2510   | 2820   | 3220   | 2970   | 3220   | 3450   | 750    | 750    | 1020   |
| Ubaye                 | 2610   | 2890   | 3150   | 2760   | 2970   | 3150   | 3030   | 3150   | 3150   | 1050   | 1050   | 1050   |

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| Region                          | 2000 | 2100 | 2200 | 2300 | 2400 | 2500 | 2600 | 2700 | 2800 | 2900 | 3000 | 3100 | 3200 | 3300 | 3400 | 3500 | 3600 | 3700 |
|--------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 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-Ariege                   | 1910 | 2050 | 2410 | 2060 | 2330 | 2790 | 2770 | 3010 | 3150 | 1050 | 1220 | 1480 | 1180 | 1410 | 1690 | 1760 | 2020 | 2590 |
| Orlu St-Barthelemy             | 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 |
| Ribagorcana                    | 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-Pirineu                    | 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 B 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).

| Resorts Features | Ski Lift Power | Size Category | Village Elevation | Mean Elevation | Max. Elevation |
|------------------|----------------|---------------|-------------------|----------------|----------------|
| Chablais (Northern Alps) |               |               |                   |                |                |
| LULLIN COL DE FEU | 81             | S             | 1084              | 1130           | 1175           |
| PLAINE-JOUX      | 749            | S             | 1372              | 1508           | 1718           |
| ABONDANCE        | 1205           | S             | 1049              | 1341           | 1758           |
| HABERE POCHE     | 1454           | S             | 1018              | 1200           | 1505           |
| BELLEVAUX HIRMENTAZ | 2115         | S             | 1185              | 1331           | 1612           |
| BERNEX           | 2372           | S             | 1009              | 1396           | 1871           |
| THOLLON LES MEMISES | 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’ARACHES (LES) | 7348         | L             | 1160              | 1561           | 2109           |
| MORZINE PLENEY NYON | 9204         | L             | 1012              | 1467           | 2127           |
| GETS (LES)       | 10489          | L             | 1202              | 1502           | 2131           |
| MORILLON-SAMOENS-SIXT | 12159       | L             | 968               | 1501           | 2118           |
| GRAND MASSIF (FLAINE - VALLEE DU GIFFRE) | 13466 | L             | 1662              | 1982           | 2482           |
| CHATEL           | 13959          | L             | 1208              | 1631           | 2093           |
| AVORIAZ - MORZINE | 18826         | XL            | 1758              | 1815           | 2501           |

Aravis (Northern Alps)
| Location                                      | Latitude | Longitude | North  | East   | West  | South |
|-----------------------------------------------|----------|-----------|--------|--------|-------|--------|
| 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) - SALLANCHE-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)                            | 11400    | L         | 1254   | 1509   | 2031  |
| CLUSAZ (LA)                                   | 13826    | L         | 1126   | 1612   | 2375  |

**Mont-Blanc (Northern Alps)**

| Location                                      | Latitude | Longitude | North  | East   | West  | South |
|-----------------------------------------------|----------|-----------|--------|--------|-------|--------|
| VALLORCINE LA POYA                            | 1503     | S         | 1358   | 1577   | 1932  |
| SAINT NICOLAS DE VEROCE                       | 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                    | 10409    | L         | 1206   | 1786   | 2437  |
| MEGEVE                                        | 15132    | XL        | 1175   | 1557   | 2014  |
| CHAMONIX                                      | 27378    | XL        | 1160   | 1938   | 3787  |

**Bauges (Northern Alps)**

| Location                                      | Latitude | Longitude | North  | East   | West  | South |
|-----------------------------------------------|----------|-----------|--------|--------|-------|--------|
| 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-MARGERIAZ                     | 3594     | M         | 1029   | 1430   | 1834  |

**Beaufortain (Northern Alps)**

| Location                                      | Latitude | Longitude | North  | East   | West  | South |
|-----------------------------------------------|----------|-----------|--------|--------|-------|--------|
| GRANIER SUR AIME                              | 224      | S         | 1394   | 1522   | 1661  |
| CREST VOLAND                                  | 3472     | M         | 1257   | 1410   | 1608  |
| Location                          | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|----------------------------------|------|------|-------------|-------------|-------------|
| ARECHES 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)**

| Location                          | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|----------------------------------|------|------|-------------|-------------|-------------|
| SAINTE FOY TARENTAISE            | 2436 | S    | 1536        | 2067        | 2612        |
| ROSIERE (LA)                     | 6969 | L    | 1841        | 2031        | 2572        |
| VAL D’ISERE                     | 24371 | XL | 1868        | 2368        | 3197        |
| TIGNES                           | 25814 | XL | 2092        | 2251        | 3459        |
| ARCS (LES) - PEISEY-VALLANDRY    | 31699 | XL | 1786        | 1826        | 3220        |

**Chartreuse (Northern Alps)**

| Location                          | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|----------------------------------|------|------|-------------|-------------|-------------|
| 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 - DESERT D’ENTREMONT (LE) | 506 | S | 1106        | 1207        | 1428        |
| SAINT HILAIRE DU TOUDET         | 517  | S    | 974         | 1075        | 1415        |
| SAINT PIERRE DE CHARTREUSE - LE PLANOLET | 2958 | M | 982         | 1318        | 1751        |

**Belledonne (Northern Alps)**

| Location                          | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|----------------------------------|------|------|-------------|-------------|-------------|
| 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)                  | 10881 | L | 1396        | 1786        | 2378        |

**Maurienne (Northern Alps)**

| Location                          | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|----------------------------------|------|------|-------------|-------------|-------------|
| 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        |
| Location                        | Code  | Region | Size | Length | Altitude |
|--------------------------------|-------|--------|------|--------|----------|
| **Vanoise (Northern Alps)**    |       |        |      |        |          |
| Notre Dame du Pre              | 226   | S      | 1279 | 1365   | 1510     |
| Aussois                        | 3055  | M      | 1535 | 2096   | 2670     |
| Pralognan                      | 3505  | M      | 1438 | 1495   | 2340     |
| Orelle                         | 5217  | L      | 2364 | 2003   | 3242     |
| Saint Francois Longchamp       | 6405  | L      | 1583 | 1904   | 2514     |
| Valmorel                       | 11005 | L      | 1382 | 1748   | 2401     |
| Meribel les Allues             | 15767 | XL     | 1362 | 1913   | 2701     |
| Val Thorens                    | 19844 | XL     | 2300 | 2501   | 3186     |
| Menuires (Les)                 | 22331 | XL     | 1798 | 2185   | 2845     |
| Pagne (La)                     | 35044 | XL     | 1849 | 2028   | 3167     |
| Courchevel                     | 39787 | XL     | 1667 | 2084   | 2919     |
| **Haute-Maurienne (Northern Alps)** | |        |      |        |          |
| Bramans                        | 16    | S      | 1261 | 1277   | 1315     |
| Bessans                        | 185   | S      | 1715 | 1849   | 2079     |
| Bonneval sur Arc               | 2024  | S      | 1831 | 2339   | 2937     |
| Val Frejus                     | 3773  | M      | 1627 | 2086   | 2731     |
| Norma (La)                     | 4032  | M      | 1387 | 1964   | 2742     |
| Val Cenis                      | 13212 | 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’)               | 18232 | XL     | 1771 | 2125   | 3318     |

**Vercors (Northern Alps)**
| Location                                      | Code | Type | Latitude | Longitude |
|-----------------------------------------------|------|------|----------|-----------|
| SAINT NIZIER                                  | 22   | S    | 45.0713  | 5.2089    |
| RENCUREL                                      | 221  | S    | 45.0017  | 5.1943    |
| COL DE L’ARZELIER                             | 472  | S    | 45.0769  | 5.2582    |
| FONT D’URLE - CHAUD CLAPIER                   | 504  | S    | 45.1042  | 5.2997    |
| GRESSE EN VERCORS                             | 1257 | S    | 45.0328  | 5.2254    |
| COL DU ROUSSET                                | 1297 | S    | 45.0492  | 5.2335    |
| AUTRANS                                       | 1535 | S    | 45.0232  | 5.2301    |
| MEAUDRE                                       | 1645 | S    | 45.0067  | 5.2257    |
| LANS EN VERCORS                               | 1880 | S    | 45.0217  | 5.2176    |
| VILLARD DE LANS-CORRENCON                    | 9644 | L    | 45.0332  | 5.2770    |

**Oisans** (Northern Alps)

| Location                                      | Code | Type | Latitude | Longitude |
|-----------------------------------------------|------|------|----------|-----------|
| NOTRE DAME DE VAULX                           | 18   | S    | 45.0265  | 5.2117    |
| VILLARD REYMOND                               | 37   | S    | 45.0400  | 5.2208    |
| MOTTE D’AVEILLANS (LA)                        | 84   | S    | 45.0257  | 5.2192    |
| SAINT FIRMIN VALGAUDEMAR                      | 91   | S    | 45.0291  | 5.2213    |
| COL D’ORNON                                   | 401  | S    | 45.0428  | 5.2255    |
| GRAVE (LA)                                    | 995  | S    | 45.0449  | 5.2203    |
| ALPE DU GRAND SERRE (L’)                      | 3225 | M    | 45.0430  | 5.2206    |
| DEUX ALPES (LES)                              | 23796| XL   | 45.0276  | 5.2204    |

**Thabor** (Southern Alps)

| Location                                      | Code | Type | Latitude | Longitude |
|-----------------------------------------------|------|------|----------|-----------|
| NEVACHE                                       | 112  | S    | 45.1297  | 5.2057    |
| MONTGENEVRE                                   | 8587 | L    | 45.1293  | 5.1882    |

**Pelvoux** (Southern Alps)

| Location                                      | Code | Type | Latitude | Longitude |
|-----------------------------------------------|------|------|----------|-----------|
| PELVOUX-VALLOUISE                             | 1391 | S    | 45.1364  | 5.1865    |
| PUY ST VINCENT                                | 5734 | L    | 45.1392  | 5.1791    |
| SERRE CHEVALIER                               | 26571| XL   | 45.1232  | 5.1943    |

**Queyras** (Southern Alps)
| STATION DU QUEYRAS | 6834 | L | 1819 | 2024 | 2801 |
|---------------------|------|----|------|------|------|
| Devoluy (Southern Alps) |
| LUS LA JARJATTE | 385 | S | 1171 | 1339 | 1521 |
| MASSIF DU DEVOLUY | 7068 | L | 1506 | 1591 | 2490 |
| Champsaur (Southern Alps) |
| ANCELLE | 1842 | S | 1351 | 1511 | 1811 |
| STATIONS VILLAGE DU CHAMPSAUR | 3907 | M | 1386 | 1486 | 2240 |
| ORCIERES MERLETTE | 8297 | L | 1836 | 2178 | 2725 |
| Embrunnais Parpaillon (Southern Alps) |
| REALLON | 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 | 17669 | 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)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| VAL D’AZUN                    | 14   | S    | 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                     | 10243| L    | 1784, 1866, 2490 |
| SAINT LARY SOULAN             | 12822| L    | 1653, 1991, 2471 |

### Aure Louron (French Pyrenees)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| VAL LOURON                    | 1693 | S    | 1462, 1723, 2058 |
| PEYRAGUDES                    | 7741 | L    | 1623, 1884, 2260 |

### Luchonnais (French Pyrenees)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| BOURG D’OUEIL                 | 109  | S    | 1345, 1438, 1498 |
| SUPERBAGNERES                 | 6446 | L    | 1792, 1736, 2133 |

### Couserans (French Pyrenees)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| LE MOURTIS                    | 1096 | S    | 1425, 1578, 1801 |
| GUZET NEIGE                   | 2673 | M    | 1445, 1600, 2050 |

### Haute-Ariege (French Pyrenees)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| AX LES THERMES                | 7437 | L    | 1398, 1955, 2948 |

### Orlu St-Barthelemy (French Pyrenees)

| Location                      | Code | Type | Elevation (m) |
|-------------------------------|------|------|---------------|
| 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)

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| Location          | Code | Country   | Head | Filled | Snowboard |
|-------------------|------|-----------|------|--------|-----------|
| Quillane (LA)     | 111  | S         | 1709 | 1752   | 1812      |
| Porte 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-Arcais     | 3897 | M         | 1792 | 2281   | 2633      |
| Grandvalira       | 19747| XL        | 1772 | 2251   | 2669      |
| Jacetiana (Spanish and Andorran Pyrenees) | | | | | |
| Astun             | 3304 | M         | 1591 | 1968   | 2249      |
| Candanchu         | 4573 | M         | 1506 | 1836   | 2283      |
| Formigal          | 11251| 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    | 21246| XL        | 1685 | 2115   | 2543      |
| Ribagorcana (Spanish and Andorran Pyrenees) | | | | | |
| Boi Taull         | 4648 | M         | 1825 | 2333   | 2741      |
| Pallaresa (Spanish and Andorran Pyrenees) | | | | | |
| Espot             | 2554 | M         | 1609 | 1997   | 2339      |
| Port Aine         | 2927 | M         | 1714 | 2160   | 2432      |
| Location                     | Code | Type | Elevation 1 | Elevation 2 | Elevation 3 |
|------------------------------|------|------|-------------|-------------|-------------|
| TAVASCAN                     | 774  | S    | 1582        | 1954        | 2220        |
| **Ter-Freser** (Spanish and Andorran Pyrenees) |      |      |             |             |             |
| VALL DE NURIA                | 1040 | S    | 1656        | 2070        | 2303        |
| VALLTER 2000                 | 2036 | S    | 1797        | 2289        | 2526        |
| **Cadi Moixero** (Spanish and Andorran Pyrenees) |      |      |             |             |             |
| LA MOLINA - Masella          | 14282| L    | 1603        | 1988        | 2527        |
| **Pre-Pirineu** (Spanish and Andorran Pyrenees) |      |      |             |             |             |
| PORT DEL COMTE               | 5301 | L    | 1624        | 2020        | 2329        |