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Research Note

Panel based assessment of snow management operations in French ski resorts

Pierre Spandre[a,b,*], Hugues François[a], Emmanuelle George-Marcelpoil[a], Samuel Morin[b]

[a] Université Grenoble Alpes, Irstea, UR DTGR, Grenoble, France
[b] Météo-France CNRS, CNRM UMR 3589, Centre d'Etudes de la Neige, Grenoble, France

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ABSTRACT

The vulnerability of the ski industry to snow and meteorological conditions accounting for snow management has been addressed regarding past conditions or under climate change scenario in most of the major destinations for skiing activities including the U.S.A and Austria, although not in the French Alps yet. Such investigations require quantitative data on snow management practices in ski resorts. So far the only information available in France was aggregated at the national level and outdated. The present study aims to provide detailed information of relevance for impact studies accounting for snow management including snowmaking and grooming facilities (ratio of equipped ski slopes, snowguns types, water storage capacity) and practices (grooming frequency, snowguns positioning, required snow depth regarding the date) in French ski resorts with respect to their characteristics. We collected information from 55 French ski resorts through a survey we set up in Autumn 2014, covering a large range of ski resorts (geographical situation, size, altitude), consistently with the dispersion of the population of French ski resorts. The participant ski resorts represent about 50% of the French ski resorts total ski lifts infrastructures. This survey confirms that the snow conditions are a major priority for ski resorts operators to provide comfortable skiing conditions, to ski back down to the village or even to connect with neighbouring resorts. The required minimum snow depth is shared by most resorts, decreasing from 60 cm in February to 40 cm in April with a minimum 40 cm to maintain regardless the date. Snowmaking also appears as the major method to mitigate the dependency to natural snow conditions. Most resorts are equipped in 2015 with very similar facilities (about 35% of ski slopes equipped) even though they indicate contrasted prospects. The survey does not outline significant differences in terms of snow management practices with respect to the size or the location of the ski resorts. Using these results together with additional information suggests that the smaller, low to medium altitude resorts show lower adaptive capacity than larger, higher altitude resorts to face the natural variability and projected changes of the climate consistently with international data. This raises the interest for further investigations for the profiling of ski resorts regarding their geographical situation, management mode or target market, with probably significant influences on their willingness to develop snowmaking facilities.

Management implications: The present study highlights several points of interest for ski resorts stakeholders.

- Resorts operators share most priorities regarding snow management to ensure the spatial continuity of ski slopes (ski lifts operation) under the worst meteorological conditions and to promote the ski resort by differentiating with direct competitors. A particularly strong attention is paid to the French academic holidays.
- The required minimum snow depth depends more on the period of the season than on the size of the resort and triggers the production of machine made snow (35% of ski slopes covered for which the facilities maximum altitude is significantly correlated to the average altitude of resorts ski lifts, slope 1.1).
- The location of a ski resort may have a significant impact on its adaptive capacity with contrasted vulnerabilities to natural snow conditions (not only due to elevation differences) and potentially further implications (relationships with host communities, financial robustness), outlining strong inequalities between ski resorts to face the current variability and projected changes of the climate.
- The access to the water volumes to produce machine made snow is already inequal between resorts, most of them relying on water reservoirs which average capacity is equivalent to a 38–48 cm snow depth on equipped ski slopes. Any evolution of the need for additional snowmaking will require proportionally higher water supply, storage and related costs.

* Corresponding author at: Université Grenoble Alpes, Irstea, UR DTGR, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France.
E-mail address: pierre.spandre@irstea.fr (P. Spandre).

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1. Introduction

Ten out of the thirty greatest ski resorts in the world are located in the French Alps leading the French ski industry to be a top ranked destination for skiing activities along with Austria, U.S.A, Italy, Switzerland or Canada (Abegg et al., 2007; Vanat, 2014). Therefore, winter tourism is a major industry and plays a fundamental role in the economy of French mountain regions (Falk, 2014; Lecuret et al., 2014). In the Savoie Mont Blanc area,[1] 20% of the gross domestic product (GDP) of the departments is generated by the winter tourism (Lecuret et al., 2014). Skiing is the most practiced activity in winter (83% of visitors), far above the second (snowshoeing, 16% of visitors) leading the ski resorts operators to pay a great attention to skiing conditions and driving the corporation to an increasingly technical and professional snow management (Fauve et al., 2002; Lecuret et al., 2014).

Ski operators originally developed grooming methods in the U.S.A (Leich, 2001) to provide comfortable and safe skiing conditions (Bergstrom & Ekeland, 2004) and to maintain the resistance of the snowpack against mechanical erosion by skiers (Fauve et al., 2002; Guily, 1991) and the natural ablation processes (Keller et al., 2004; Rixen, Haeberli, & Stoeckli, 2004). Emile Allais first imported the method to France in the 1950's in Courchevel (French Alps) and as far as we know all ski resorts groom their ski slopes in 2015. Yet grooming can not compensate the possible deficit of natural snowfalls due to the interannual variability of meteorological and snow conditions (Beniston, 1997; Durand et al., 2009a). The consecutive seasons with poor snow conditions in the late 1980's in the european Alps (Durand et al., 2009b) revealed the vulnerability of ski resorts to the lack of natural snow and marked the kick-off for the development of snowmaking facilities in France (Spandre, François, Morin, & George-Marcelpoil, 2015). The competition with international destinations or alternative tourism activities (Morrison & Pickering, 2013) and the priority of specific periods (e.g. Christmas or February holidays) for the economic success of a season (Breiling & Charamza, 1999; Falk & Hagsten, 2016; Scott, McBoyle, Minogue, & Mills, 2006) encouraged ski resorts to mitigate their dependency to the meteorological and snow conditions through snowmaking facilities (Hopkins, 2015; Trawöger, 2014). Most resorts also rely on technological innovations to either adopt this strategy or produce snow in increasingly marginal conditions (Beniston, 2006; Hopkins & Maclean, 2014; Hopkins, 2015; Marke et al., 2014).

Concurrently with the snowmaking expansion, the economy of snow-related activities has been discussed in present time and under future potential climate conditions using several indicators such as the ski lifts tickets sales (Falk, 2014; Koenig & Abegg, 1997), the overnight stays of consumers in ski resorts (Falk, 2010; Töglhofer, Eigner, & Prettenthaler, 2011) or in terms of contribution to the gross domestic product (Damm, Koeberl, & Prettenthaler, 2014). A major challenge of researchers intending to assess the vulnerability of snow-related economy to climate change is to associate these indicators with climate dependent factors such as the mean snow depth (Falk, 2014), the number of days with snow on the ground (Töglhofer et al., 2011), with a minimum snow depth (François, Morin, Lafaysse, & George-Marcelpoil, 2014; Hanzer, Marke, & Strasser, 2014; Schmidt, Steiger, & Matzarakis, 2012; Scott, McBoyle, & Mills, 2003) or snow mass (Marke et al., 2014). Due to the difficulty to combine such transdisciplinary approaches (Strasser et al., 2014) and to compare the results from different combinations of indicators (Neuvonen et al., 2015), a standard definition of the snow reliability of ski resorts was established, combining snow depth and season length, the so-called “100 days” rule (Elsasser & Bürki, 2002; Scott et al., 2003). This was used to address the snow reliable altitude of a region (Abegg et al., 2007; Elsasser & Bürki, 2002), the decline of the ski season length due to climate change or the required amounts of machine made snow to compensate the loss (Scott et al., 2003; Steiger, 2010) even though the required snow depth may depend on the region (Pons-Pons et al., 2012; Scott & McBoyle, 2007) or on the period of the season (Damm et al., 2014; Hanzer et al., 2014; Hennessy et al., 2007). The adaptation of the ski industry to climate change through snowmaking has been studied in Australia (Hennessy et al., 2007), New-Zealand (Hendrikx & Hreinsson, 2012), Andorra (Pons-Pons et al., 2012), Spanish and French Pyrenees (Pons, López-Moreno, Rosas-Casals, & Jover, 2015), Germany (Pröbstl, 2006; Schmidt et al., 2012), Switzerland (Rixen et al., 2011), Austria (Damm et al., 2014; Steiger, 2010; Töglhofer et al., 2011), U.S.A. (Dawson & Scott, 2013) and Canada (Scott & McBoyle, 2007; Scott et al., 2003).

Surprisingly French and Italian Alps are major areas within the international skiing market where little investigation has been undertaken and has been limited to the analysis of past conditions and under natural snow conditions (Abegg et al., 2007; Elsasser & Bürki, 2002; François et al., 2014). Until recently there was no snowpack model able to handle snow production or grooming over the French Alps (Spandre et al., 2016) in addition to the prohibitive lack of information on snowmaking facilities in ski resorts (François et al., 2014). To the best of our knowledge there is no publication describing the French grooming facilities and practices, and the latest investigation on snowmaking facilities is limited to the ratio of equipped ski slopes with snowguns aggregated at the national level and based on data from the 2007 to 2008 winter season (Badré et al., 2009). Such limitations hampered any investigation, either in the past or under future climate projections, of snow conditions in French ski resorts accounting for snow management which require more detailed information on profesionnal practices (Hanzer et al., 2014; Scott & McBoyle, 2007; Spandre et al., 2016). The present study therefore aims to question the general priorities of French ski resorts operators and how these influence their habits and facilities in terms of snow management with respect to the existing international data (Abegg et al., 2007; Hennessy et al., 2007; Scott et al., 2003, Section 2). We also provide detailed information on the snowmaking and grooming facilities (ratio of equipped ski slopes, snowguns types, water storage capacity) and practices (grooming frequency, snowguns positioning, required snow depth regarding the date) in French ski resorts with respect to their characteristics (altitude, size and location).

Our analysis is based on a survey of a panel of 55 French ski resorts carried out in autumn 2014 and a specific database on French Alps ski resorts, allowing the analyze of the survey's results based on resorts features (Section 3). We identify the main priorities of ski resorts operators and the main drivers of the current practices and facilities in terms of grooming and snowmaking (Section 4), including their potential evolution until 2020. Last, we discuss the relationships between the vulnerability to natural snow conditions from François et al. (2014) of sample ski resorts and their current level of equipment in snowmaking facilities with respect to their main features, intending to provide a synthesis framework for the analysis of the development of snowmaking facilities within French ski resorts (Section 5). The limitations of the survey's setup and results are also discussed.

2. Literature review

2.1. Grooming impact and interest for stakeholders

The grooming of ski slopes is a fundamental method for the preparation of ski slopes shared by almost all resorts (Fauve et al., 2002). Grooming significantly affects the snowpack properties (De Jong et al., 2015; Fahey et al., 1999; Howard & Stull, 2014; Keddy, 1979; Keller et al., 2004; Mossner et al., 2013; Rixen et al., 2004). Fahey et al. (1999) monitored four groomed slopes and found that the average density was 36% higher on groomed slopes with respect to control slopes (ungroomed). Mossner et al. (2013) reported values

[1] French departments of Savoie (73) and Haute-Savoie (74).

from 344 measurements of snow density on ski slopes ranging between 420 and 620 kg m^{-3} with a mean value of 556 kg m^{-3}. Since the snow thermal conductivity (Calonne et al., 2011) and hardness (Howard & Stull, 2014; Keller et al., 2004) are strongly related to the density of snow, the enhancement of the snow density due to grooming affects both the thermal and mechanical behavior of the snowpack. Rixen et al. (2004) observed on ten sites with groomed snow an average 1 °C difference of the ground temperatures compared with ungroomed slopes, leading to soil frost in several occasions. Such changes in the thermal behavior of the snowpack delay the melt-out date by several weeks (Keller et al., 2004; Rixen et al., 2004). Concurrently Keller et al. (2004) reported from both observations and modelling of groomed snowpack conditions that the penetration force increased by a factor of ten when snow density doubled from 200 to 400 kg m^{-3}. Therefore grooming lengthens the ski season and enhances the resistance of the snowpack to the erosion by skiers (Federolf et al., 2006). In addition, Bergstrom and Ekeland (2004) concluded from a record of the injuries during seven winter seasons in a ski resort in Norway that grooming has a significant and positive impact on the rate of injuries, resulting in decreasing injuries with increasing grooming. Finally, Fauve et al. (2002) summarized the interest of grooming from interviews with professionals and literature review: ski slopes are made safer, uniform (no surprises), have a good “grip” (no ice), are visually attracting and resistant against erosion or meteorological conditions.

2.2. Variability, climate change and snowmaking

Durand et al. (2009b) analyzed 47 years of climate conditions from a combined approach of modelling and observations and outlined a significant spatial and temporal variability of the natural snow conditions in the French Alps. This variability was found maximum for mid-altitudes, about 1500 m.a.s.l. Such variability of the snow conditions was also reported in the European Alps (Beniston, 1997; Gobiet et al., 2014) or in North America (Hughes & Robinson, 1996). Most projections of the impact of climate change also indicated that the interannual variability is likely to remain very significant in coming decades (Castebrunet, Eckert, Giraud, Durand, & Morin, 2014; Kotlarski et al., 2014; Marke et al., 2014; Rousselot et al., 2012). François et al. (2014) investigated the natural snow conditions in French Alps ski resorts accounting for the geographical features of resorts (altitude, slope aspect) and calculated a viability index as the share of the ski area encountering more than 30 cm of snow for at least 100 days. The viability of small resorts ranged between 18% and 90% while very large resorts showed viability index between 65% and 97% over the 2001–2012 decade. The vulnerability of ski resorts to the variability of the natural snow conditions were confirmed in all alpine countries (Abegg et al., 2007; Elsasser & Bürki, 2002). Falk (2010) estimated from a panel of 28 Austrian resorts and for the period 1986–2005 that the number of visitors in resorts with ski slopes below an altitude of 2000 m.a.s.l. decreased with snow depth even though snowmaking mitigated the magnitude of the impact. On the base of a large panel of Austrian ski resorts and over a long period of time (1972–2007), Töglhofer et al. (2011) estimated that a one standard deviation increase in snow conditions (mean snow depth, days with snow on the ground and days when snow depth exceeds 30 cm) leads to a 0,6 to 1,1% increase in overnight stays. Similarly to Falk (2010), this relationship was highlighted for resorts with a mean altitude below 1800 m.a.s.l. otherwise a negative relationship was found. Concurrently, Trawöger (2014) concluded from interviews of 24 experts (CEOs of tourism associations or cable car companies) in the Austrian Alps that the dependency to natural snow conditions was the major driver of the development of snowmaking in ski resorts and Hopkins (2015) highlighted the same role of snowmaking in interviews of a sample of 14 ski industry stakeholders in the region of Queenstown (New-Zealand). In 2005, 16% of ski slopes were equipped with snowmaking facilities in France, 50% in Austria, 18% in Switzerland and 40% in Italy according to Abegg et al. (2007). This ratio may have risen in 2015 to 32%, 70%, 48% and 70% respectively in France (Spandre et al., 2015), Austria, Switzerland and Italy (Seilbahnen Schweiz, 2015). However Hopkins and Maclean (2014) concluded from interviews of stakeholders in five ski resorts in Scotland that some regions were not able to produce machine made (MM) snow (Fierz et al., 2009) due to inadequate meteorological conditions.

The recent developments of snowmaking facilities also reveal a confused and contradictory perception of climate change (Hopkins & Maclean, 2014; Hoy, Hänsel, & Matschullat, 2011; Trawöger, 2014) and a sharp awareness by ski resorts operators that the perception of their vulnerability to climate change may be more damaging than its actual impacts (Dawson & Scott, 2013; Morrison & Pickering, 2012) resulting in a corporate strategy concerning snowmaking. On one hand ski resorts operators downplay the risks of insufficient natural snowfall or do not consider climate change as a major threat (Hopkins & Maclean, 2014; Morrison & Pickering, 2012; Trawöger, 2014; Wolfsegger, Gössling, & Scott, 2008), on the other hand they justify further developments by highlighting the use of machine made snow as a relevant adaptation method against climate change and variability (Morrison & Pickering, 2012; Trawöger, 2014), although low altitude resorts remain negatively impacted by seasons with poor snow conditions (François et al., 2014; Pickering, 2011; Schmidt et al., 2012). On the contrary high altitude resorts do not show any (Falk, 2010) or even negative (Koenig & Abegg, 1997; Töglhofer et al., 2011) dependency to the snow conditions, although they invest in snowmaking facilities (Falk, 2014) and use MM snow as a sales pitch (snow guarantee). The largest French ski resorts are likely to be the most equipped in 2020 (50% of ski slopes covered by snowguns, Spandre et al., 2015). The development of snowmaking facilities is therefore expected to remain highly individualistic (Scott & McBoyle, 2007; Trawöger, 2014).

Most investigations of the climate change impact concluded that the ski season length will decrease even if machine made snow is produced (Marke et al., 2014) and that snowmaking may not be a relevant adaptation method beyond the short-term period (Morrison & Pickering, 2013; Pickering, 2011; Schmidt et al., 2012) due to the associated environmental impact (De Jong et al., 2015), increasing water demand (Vanham, Fleischhacker, & Rauch, 2009) and rising costs of energy (Damm et al., 2014). Hennessy et al. (2007) estimated the suitable hours for snowmaking and the machine made snow requirements to ensure skiable conditions in six Australian ski resorts and concluded that snowmaking was a relevant method until the 2020's but may not be sufficient by 2050, depending on the climate change scenario. Similarly Steiger (2010) investigated the impact of climate change on three ski resorts in Tyrol (Austria) and concluded their operation would remain reliable until the 2040's through snowmaking. By then, significant uncertainties exist particularly for low altitude resorts even accounting for snowmaking (Steiger, 2010). Pons-Pons et al. (2012) addressed the viability of three high altitude ski resorts in Andorra (>1900 m.a.s.l) and concluded that all three would remain reliable under a +2 °C rise of temperatures but may not under a +4 °C increase.

2.3. Snow management processes

Most investigations of snow management built up synthetic approaches to govern snowmaking to estimate the required amounts of machine made snow to achieve satisfying skiing conditions, particularly regarding the impacts of climate change (Scott & McBoyle, 2007; Scott et al., 2003; Steiger, 2010). Since most snow models that have been used can not account for the impact of grooming, little attention has been paid to model the grooming process (Hanzer et al., 2014; Pons-Pons et al., 2012; Scott et al., 2003; Steiger, 2010). Beyond modelling physical processes within the snowpack (Howard & Stull, 2014; Spandre et al., 2016), distinct frameworks (periods of production, snow-base layer) and thresholds (triggering temperature and snow depth) have been used to model the snowmaking process. Pons-Pons et al. (2012); Scott and McBoyle (2007); Scott et al. (2003); Steiger (2010) used the dry-air temperature to control the production decision (threshold of −5 °C or −2 °C) and Rixen et al. (2011) the dew-point temperature (threshold of −4 °C) while the most relevant meteorological parameter which is used by professional snowmakers is the wet-bulb temperature T_w (Hanzer et al., 2014; Olefs, Fischer, & Lang, 2010; Spandre et al., 2016). The technical threshold indicated by snowguns manufacturers is $T_w = -2$ °C (Hanzer et al., 2014; Olefs et al., 2010) while practices by professional snowmakers may differ (Hendrikx & Hreinsson, 2012; Spandre et al., 2016).

The snow depth usually considered to provide skiable conditions and thus producing snow in case of insufficient natural snow usually refers to the “100 days rule” which states that a ski resort operation is viable if the snow depth exceeds 30 cm for at least 100 consecutive days of the winter season (Elsasser & Bürki, 2002; Scott et al., 2003). Scott et al. (2003) used a 50 cm target snow depth to estimate the required snowmaking amounts in Southern Ontario, Scott and McBoyle (2007) a 60 cm target in Québec and Pons-Pons et al. (2012) a 30 cm target in Andorra. All three investigations used start (22 November) and end dates for snowmaking (30 March). Hennessy et al. (2007) divided the season within five months (from opening to closing dates) with a corresponding target snow depth for each month which they defined with the ski resorts operators (from 20 cm increasing to the maximum 100 cm in the middle of the season and decreasing again until 20 cm in the late season). Alternatively, Schmidt et al. (2012); Steiger (2010) defined a minimum amount of machine made snow to be produced regardless the natural snow conditions, the “base layer” (30 cm) and then a minimum snow depth to maintain (30 cm). Start and end dates for snowmaking are respectively the 1 November and the 30 March. Similarly Damm et al. (2014); Hanzer et al. (2014) in Austria divided the winter season into two periods: the “base layer” snowmaking period (1 November to the 15 December) when the model can produce as much snow as possible and the “improvement snowmaking” period (16 December to the 28 February) when a minimum snow depth is maintained (60 cm). Regarding the diversity of modelling approaches of snowmaking, covering Australia, Austria, U.S.A. and Canada, detailed information for French ski resorts is clearly missing for any investigation of the impacts of snow management on snow conditions.

Based on a survey of a sample of 55 French ski resorts (Section 3), the present study therefore questions the general priorities of stakeholders and provides detailed information on snowmaking and grooming facilities in the French Alps (Section 4). We further discuss how the priorities pursued by stakeholders drive the current practices and facilities in terms of snow management and the relevance of these relationships regarding resorts features, including their vulnerability to natural snow conditions from François et al. (2014), intending to provide a synthesis framework for the analysis of the development of snowmaking facilities within French ski resorts (Section 5).

3. Methods and definitions: structural data on ski resorts and treatment of survey's results

3.1. Professionals survey and the socio-economic database “BD Stations”

An online survey towards professionals was set up in Autumn 2014 and sent to 161 contacts of managers of technical services of ski resorts. The national association of ski patrol managers (ADSP, standing for “Association Nationale des Directeurs de Pistes et de la Sécurité des stations de Sports d'Hiver”) provided these contacts. A code was dedicated to every contact to guarantee a personal access to the survey as well as the confidentiality of data. The survey was closed on 9 January 2015. Data from the socio-economic database “BD Stations” (Marcelpoil et al., 2012) were used to assess the representativity of the survey's sample among all French Alps resorts and to analyze the survey's results. The “BD Stations” is a powerful tool to support investigations focused on large territories where winter sports are an activity among many others or zoomed at the scale of a single ski-lift (François et al., 2014; Spandre et al., 2015). The database includes geographical representations of ski slopes surfaces named “gravitational envelopes” (Francois et al., 2016) and structural data on ski lift referred to as the ski-lift power (SLP) and defined as the product of the elevation difference between the bottom and the top of a ski lift (in km) and its flow of persons per hour (pers h^{-1}). The aggregated SLP of a ski resort is a relevant indicator of its size which is used by “Domaines Skiables de France” (DSF), the French national association of ski resorts to distinguish four resorts categories (Table 1 and François et al., 2014).

3.2. Treatment method of the survey's results

Several indicators have been used to analyze the results of the survey, depending on the question type.

- The simple average of resorts answers;
- The weighted average of the resorts answers by the resort ski lift power;
- The integrated result for a given category of the answers of all resorts belonging to this category. For example, the ratio of the equipped surface with snowmaking facilities for each category is calculated as the sum of equipped surfaces with snowmaking facilities of each resort of the category divided by the sum of the surface of ski slopes of each resort of the category.

The term of ski slopes (or ski field, as the sum of all ski slopes of a resort) we refer to in the following sections corresponds to the ruled, protected and marked slopes of a ski resort and excludes any other slopes that may be accessed from ski-lifts (off-piste).

3.3. Diversity and representativity of the sample ski resorts

56 ski resorts participated to the survey. 18 of them participated the day of the general assembly of the ADSP association, on the 7 October 2014. Most participant ski resorts are located in the French Alps: 11 in the Southern Alps[2] and 33 in the Northern Alps[3] among which 21 located in Savoie (73). Consistently with the distribution of ski resorts in French mountain regions, 8 participant ski resorts are located in the Pyrenees[4], two in the Jura[5], one in the Massif Central[6] and one in the Vosges[7]. Since the ski resort located in Andorra does not depend on the STRMTG national service (“Service Technique des Remontées Mécaniques et des Transports Guidés”), no data were available in the “BD Stations” to analyze its answers and we could not account for its results.

The 55 resulting resorts represent 25% of the 220 French ski resorts in total (DSF, 2011), only 5% of the French small resorts (S) are represented against 38% of the medium, 65%, of the large (L) and 62% of the very large resorts (XL). Even though the majority of French ski

Table 1
Ski resorts categories regarding the ski lift power (François et al., 2014).

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Ski Lift Power (SLP) (km pers h^{-1})	SLP < 2500	2500 < SLP < 5000	5000 < SLP < 15000	15000 < SLP

resorts are small, their aggregated SLP is low compared to the other categories (7% of the national SLP, 2% of the sample SLP). The sample of ski resorts participating to the survey represents 51% of the French total SLP. There is a large dispersion of the SLP, average age and altitude of ski resorts within each category (Fig. 1, Table 2) which Spandre et al. (2015) showed to be consistent with the dispersion within the total population of alpine resorts for each category (Marcelpoil et al., 2012) suggesting that the results of this survey can be considered in a large extent as representative of the French ski resorts.

3.4. Description of the ski fields of the sample ski resorts

There is a significant relationship between the ski-lift facilities of a ski resort (SLP) and the offer in terms of potential surface of ski slopes (Table 2): the ratio of the skifield surface to the SLP of a resort proves relatively stable for the largest categories (M to XL) with 0.020 ha (km pers h^{-1})$^{-1}$. The average altitude and age of ski-lifts are also related to the size of a ski resort: the larger the resort, the higher and the more recent the ski-lifts (Fig. 1 and Table 2). This relationship can also be noticed in the geographical pattern of the sample ski resorts: 6 out of the 8 very large resorts are located in Savoie and the 16 largest resorts of the sample are located in the Northen Alps (Fig. 1). The average ski-lift power of sample ski resorts located in Savoie is 11,400 km pers h^{-1} and respectively 10,500, 5600, 4200 and 4600 km pers h^{-1} in the Northern Alps outside Savoie, in the Southern Alps, in the Pyrenees and in the other mountains of France. In Savoie, the average age of ski lifts is 18.7 years old and the average altitude of sample ski resorts is 2110 m.a.s.l. In the Alps (outside Savoie) and in the Pyrenees, the average age of ski lifts range between 21 and 22 years old and average altitude between 1860 and 2020 m.a.s.l. The four resorts located in the other mountains of France have an average age of 27 years old and an average altitude of 1290 m.a.s.l. The sample of ski resorts outlines the strong geographical pattern of ski resorts in France: the largest French ski resorts benefit from the youngest ski lifts in the highest areas and are first located in Savoie then in the rest of the Northern Alps and last in the Southern Alps, the Pyrenees and other mountains of France.

4. Results: snow management priorities of ski resorts operators and associated facilities

4.1. Self-assessment of snow and economic conditions by ski resorts operators

Distinct patterns between categories may also be revealed by the perception by ski resorts operators of their own economic situation and vulnerability to snow conditions (Fig. 2). In the case of small resorts, the economic situation is seen as related to the snow conditions while for a given perception of the snow conditions the medium resorts indicate contrasted perceptions of the economic situation of their resort. For example, nine medium resorts indicate that the average snow conditions are “Good”, three of them think the economic situation of the resort is “Weak” and two estimate it is “Very Good”. In the case of large resorts, they do not perceive significantly better snow conditions compared to medium resorts but the economic situation is one step better (“Fair” as a minimum). A similar analysis can be drawn from the answers of very large resorts: they do not have a better perception of their own snow conditions than large or even medium resorts but the economic situation is seen as “Good” or “Very Good”. Consistently with the diversity in resorts characteristics, their perception of the economic situation and vulnerability of the resort to snow conditions appear constrated.

4.2. General priorities of resorts stakeholders

Several priorities can be distinguished for ski operators and summarized in three items: to satisfy the skiers expectations, to provide technical solutions and to promote the resort. The satisfaction of skiers expectations is the major priority for ski resorts operators i.e. to provide comfortable skiing conditions (mark 9.0/10 over all resorts) and to allow to return back down the village by ski (mark 8.8/10). The second priority is to build a snowpack resistant to the erosion by skiers and meteorological conditions (mark 8.2/10) to guarantee skiable conditions during the longest possible period. Since grooming may provide such suitable conditions, the main constraint is to maintain a sufficient snow depth on ski slopes (mark 8.1/10), by producing snow if necessary. Last, the promotion of the resort is an important purpose. Every morning the ski slopes should have a visually attracting appearance (mark 8.1/10) and, if relevant, the connection with neighbouring resorts should be guaranteed. Connectivity with another resort is the only item with significantly contrasted results between categories: 2.4/10 (small resorts), 4.7/10 (medium resorts), 7.1/10 (large resorts) and 9.3/10 (very large resorts). This result can be due to the rising probability to have a connecting resort with the size of a given ski resort. We may also explain it by the increasing promotion of ski resorts through the size (e.g. km of ski slopes) which skiers may consider rewarding. The “Trois vallées” ski resort (gathering Méribel, Val Thorens and Courchevel) announces the “largest ski resort in the world”. Similarly Paradiski (made of Les Arcs and La Plagne) promotes the “second largest ski resort in the world” and l′Espace Diamant (Val d′Arly, Beaufortain) offers to skiers to “leapfrog over resorts” (source: web sites).

Such priorities provide a background for the interpretation of most practices of grooming and snowmaking described in further sections. As the major priority, the satisfaction of skiers expectations can be fulfilled through safe, comfortable and attractive snow conditions by grooming ski slopes (Bergstrom & Ekeland, 2004; Keller et al., 2004) and providing, if necessary, additional snow until sufficient through snowmaking (Scott et al., 2003; Steiger, 2010).

4.3. Grooming operations and facilities

Facilities related to ski resorts size. As far as we know, all ski resorts groom their ski slopes, which is the case for the sample ski resorts. The frequency of grooming is very similar between resorts: about 2/3 of the total ski field is groomed every day in medium and large resorts, 77% in very large and 80% in small resorts. There is no significant relationship between the grooming frequency and schedule (data not shown) with the size of the ski resort. This is consistent with the priorities regarding the snowpack properties which are shared by all ski resorts. As a consequence, the grooming facilities are significantly related to the skifield surface area: 19.2–19.9 hectare of ski slopes per grooming machine for small to large resorts and 22.4 ha for very large ski resorts. The larger surface covered by a single machine and the higher number of full time positions per machine (data not shown) in very large resorts reveals a more intense operation and a larger intention to optimize the investments in grooming facilities.

Optimization of grooming operations. Over two thirds of the sample ski resorts indicated that they intend to reduce grooming costs either by enhancing the process efficiency (faster grooming, technological innovations, etc.) or reducing the surface of groomed ski slopes. Concurrently 20% of ski resorts are equipped in 2015 with onboard

[2] Departments Alpes-de-Haute-Provence (04), Hautes-Alpes (05), Alpes-Maritimes (06).

[3] Departments Isère (38), Savoie (73), Haute-Savoie (74).

[4] Departments Ariège (09), Haute-Garonne (31), Pyrénées-Atlantiques (64), Hautes-Pyrénées (65), Pyrénées-Orientales (66) and Andorra.

[5] Department Jura (39).

[6] Department Cantal (15).

[7] Department Vosges (88).

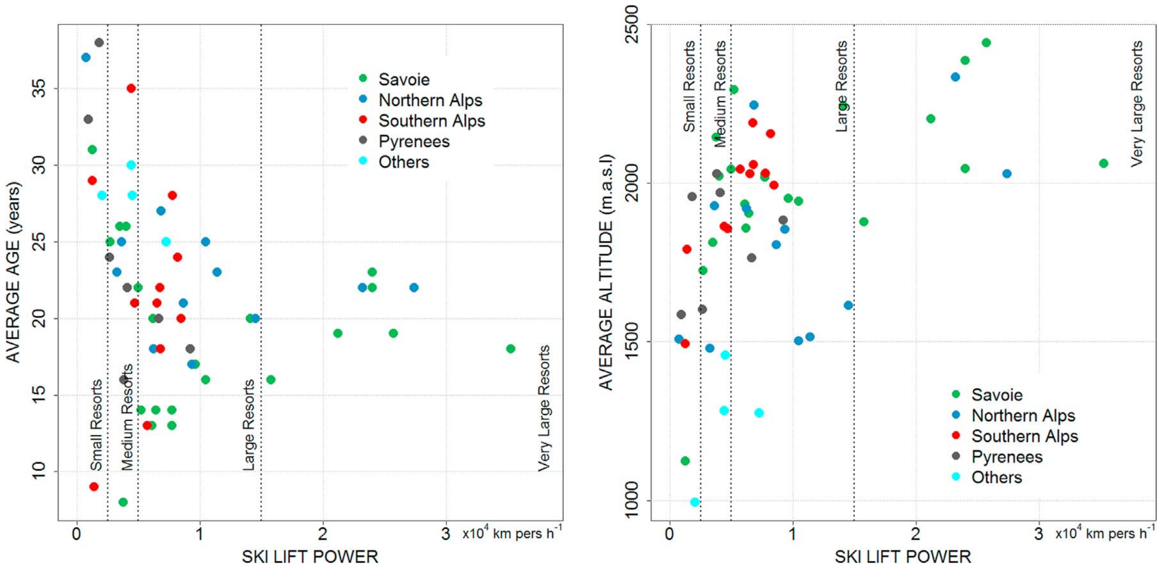

Fig. 1. Average Age and Altitude of ski-lifts of the participant ski resorts. Data from the "BD Stations" database. The category "Northern Alps" includes here all resorts in the northern Alps outside Savoie i.e. in Isère and Haute-Savoie (N=12 resorts). "Others" includes here the resorts from Jura, Cantal and Vosges of the sample ski resorts (N=4).

Table 2
Average characteristics of ski resorts which participated to the survey, weighted by the SLP (± the standard deviation). The age, altitude and ski lift power data from the "BD Stations" database.

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Ski slopes surface (ha)	**70** ± 36	**99** ± 44	**172** ± 98	**437** ± 254
Ski slopes length (km)	**37** ± 20	**64** ± 29	**122** ± 56	**221** ± 105
Ski slopes width (m)	**20** ± 8	**18** ± 8	**16** ± 9	**20** ± 10
Average Age of ski-lifts (years)	**26** ± 10	**23** ± 8	**19** ± 8	**20** ± 5
Average Altitude of ski-lifts (m.a.s.l)	**1480** ± 600	**1810** ± 450	**1910** ± 550	**2180** ± 500
Ski lift power (SLP, km pers h^{-1})	**1350** ± 870	**3900** ± 1330	**8250** ± 5250	**24,600** ± 11,260

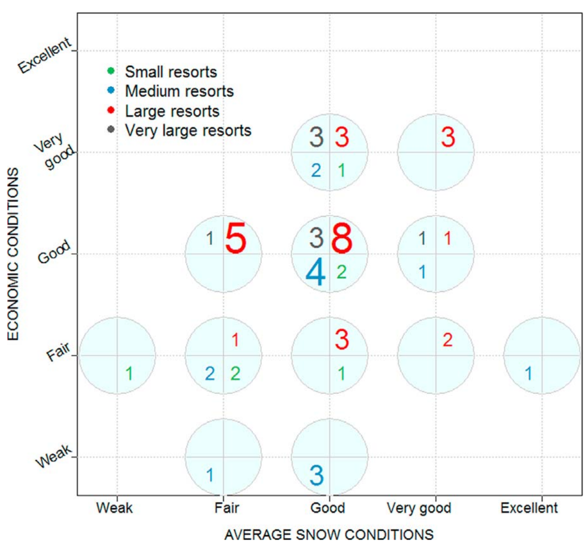

Fig. 2. Perceptions of the economic situation of the ski resorts vs. the perceived snow conditions by ski resort operators. For each category the number of resorts is indicated

measurements of the snow depth and 50% of the non equipped resorts consider it. In 2015, a majority of very large (75%) and a few large resorts (20%) are already equipped. Such systems help in optimizing not only the work done by grooming machines but more importantly the need for machine made snow that can be addressed from the difference between the measured snow depth and the required snow depth for skiing.

4.4. Managing the snow depth over the season: the driver for snowmaking

Driving snowmaking. Maintaining a sufficient snow depth is as a major priority for skiing activities (mark 8.1/10) by ski resorts operators. The required snow depth for skiable conditions does not significantly depend on the size of the resort: small resorts indicate a minimum of 42 cm, medium resorts 49 cm and large and very large resorts a minimum 46 cm (average). Concurrently, ski resorts indicate that reaching a specific snow depth at a given date is not as important (mark 5/10 for fmall resorts, 6/10 for large resorts and 7/10 for large and very large resorts). However 49 of the participant ski resorts provided a specific snow depth and date to this question (Fig. 3). Five of them focus on the early season (average target date on the 15 December, Fig. 3).

All answers together show a significant decreasing need for snow depth with time in the snow season, similarly to Hennessy et al. (2007). We removed the minimum (20 cm) and maximum (100 cm) snow depths to build a linear interpolation of the 38 remaining results (slope −0.37 cm day^{-1}, R^2=0.33). The relationship is statistically significant (p-value=10^{-4}, coefficient − 0.57 in the 95% interval) according to the Pearson's product moment correlation test (Onwuegbuzie et al., 2007). The linear model reveals that the target snow depth decreases by 11 cm per month with targets on the 1 February, 1 March and 1 April of respectively 62, 52 and 40 cm. The calculation of the target snow depth with the corresponding date in February provides a 63 cm average snow depth. This is very consistent with Scott and McBoyle (2007) and Hennessy et al. (2007).

Interestingly, a geographical pattern exists for the 44 remaining answers with a stronger focus on the early February by sample ski resorts located in the Pyrenees (average target date on the 10 February,

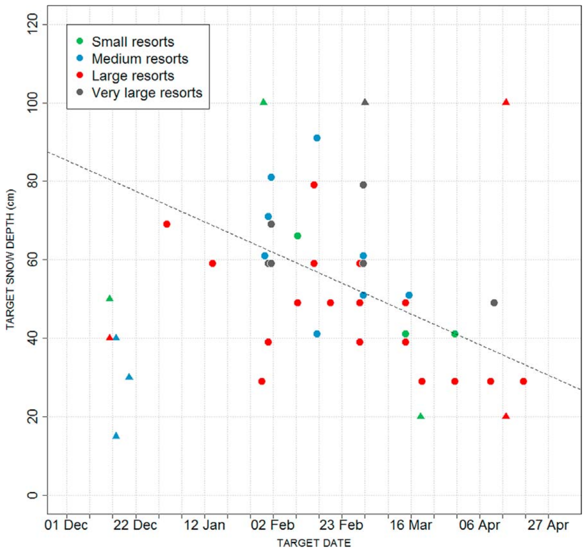

Fig. 3. The target snow depth versus the target date to reach it. The linear model does not account for the triangular points which we either related to opening constraints

similar in Jura, Cantal and Vosges), on the heart of the winter season in the Northern Alps (24 February) and late season in the Southern Alps (12 March). These dates can be compared to the records of French academic holidays, available online since the 1960s (Ministère de l'Education Nationale de l′Enseignement Supérieur et de la Recherche, 2016). On average the Christmas and New Year holidays have begun the 20 December and ended on the 5 January (± 2 days, standard deviation). From the 1990's the French academic winter holidays have begun on average the 8 February and ended on the 9 March (± 4.5 days).

Triggering of snowmaking. The wet-bulb temperature (combining the dry-air temperature and the air humidity) is used to trigger the production of MM snow (Olefs et al., 2010) with a technical threshold (from snowguns manufacturers) of −2 °C and higher efficiencies at lower temperatures (Hanzer et al., 2014; Olefs et al., 2010). The usual thresholds used by the resorts sample range between −3.2 °C (small resorts) to −4.0 °C (very large resorts). Most resorts are also prepared to produce snow one or two months ahead the opening date of the ski resort (data not shown), although the date is contrasted between categories with earlier dates for larger resorts:

- 15 October–15 November for Large and Very Large resorts
- 1–15 November for Medium resorts

4.5. Snowmaking facilities and production capacity with respect to ski resorts size

Current facilities. Only one small resort among the 55 participant ski resorts does not have any snowmaking facilities and explains this is both a conviction and a commercial argument which constitutes an original approach. Otherwise, the medium to very large resorts are currently equipped at very similar levels, around 35% (Table 3). Small resorts are less equipped with about 18% of their ski slopes covered. Focusing on the location of resorts, the ratio of equipped ski slopes with snowmaking facilities is similar in the Northern Alps (32%), in the Pyrenees (31%) and in the Jura, Cantal and Vosges ski resorts (35%). This ratio is significantly higher in the Southern Alps (41%). Similarly to previous investigations (Badré et al., 2009) the survey confirms that air/water guns are preferred to fan guns in France (Table 3) with an average 2.5–3.1 snowguns per hectare of equipped ski slopes.

Water supply. The supply of water is ensured in most cases by specific reservoirs (Peyras et al., 2010) dedicated to MM snow production (Fig. 4): 38 ski resorts among the 54 which produce MM snow have built reservoirs for water storage. One third of these resorts (17 out of 54) have this only source of water for MM snow production: the reservoirs are probably filled with snowmelt water in summer and autumn (Marnezy, 2008). An additional 19 resorts combine it with drinking water supply (DWS) or natural waterways or both. The total reservoir volume with respect to the surface equipped with snowmaking facilities does not depend on the size of the resort (Table 3): 1500–1800 m^3 of water per hectare i.e. 150–180 kg of water per m^2 of equipped ski slope. The capacity of reservoirs in the 17 ski resorts of the sample where this is the only source of water is 190 kg of water per m^2 of equipped ski slopes with snowmaking facilities with a maximum of 390 kg of water per m^2.

Evolutions. On one hand resorts operators intend to reduce the costs of snowmaking (over two thirds of the participant resorts), either by optimizing the production (85% indicate they record the volume of water used for production) or by increasing the process efficiency (automation, technological innovations, Hopkins, 2015), on the other hand most resorts indicated that they plan to extend their snowmaking facilities within an average five years (Table 4).

Focusing on the geographical location of ski resorts, the rate of increase from 2015 to 2020 of the surface equipped with snowmaking facilities is 44% in the Northern Alps, 29% in the Southern Alps and 12–15% in the Pyrenees and the Jura, Cantal and Vosges.

The resulting surface equipped with snowmaking facilities (assuming the total ski field surface does not change) may reach 34–49% of the total ski field surface for respectively the Small to Very Large resorts categories (Table 4). As long as all ski slopes are not entirely equipped with snowmaking, choices have to be made to spread out the facilities within the resort to guarantee the opening and closing dates and the way back down to the village by ski (Section 4.2). A detailed description of the positioning of facilities and the criteria to trigger the production are provided in the following section.

Spatial positioning of snowguns. The smaller the resort, the stronger attention is paid to the positioning of snowmaking facilities within the resort (Table 5). More than two thirds of the Small or Medium resorts indicated they gave priority to lower altitude areas while only 25% of Very Large did. Overall 30 resorts out of 54 indicated a maximum altitude for the installation of snowguns. This maximum altitude of snowmaking facilities (when provided) was plotted versus the average altitude of the ski-lifts of the resort from the “BD Stations” database (Fig. 5). The slope of the linear model is 1.1 (R^2=0.65) i.e. the maximum altitude of snowmaking facilities is hardly higher than the average altitude of the ski-lifts for a given resort. The relationship is statistically significant (p-value=10^{-7}, coefficient 0.81 in the 95% confidence interval) according to the Pearson's product moment correlation test (Onwuegbuzie et al., 2007). The analysis of preferred slopes (in terms of angular aspect) does not show any significant

Table 3
Current snowmaking facilities in ski resorts, by integrating results for each category (± the standard deviation).

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Ski slopes surface equipped with snowmaking facilities (%)	**18** ± 25	**34** ± 16	**35** ± 21	**34** ± 24
Number of air/water guns per surface of equipped ski slopes (ha^{-1})	**3.1** ± 2.5	**2.5** ± 1.1	**2.6** ± 1.7	**3.0** ± 0.8
Number of fan guns per surface of equipped ski slopes (ha^{-1})	**0.4** ± 0.3	**0.2** ± 0.3	**0.2** ± 0.2	**0.1** ± 0.1
Total reservoirs capacity per surface of equipped ski slopes (m^3 ha^{-1})	**1450** ± 2350	**1800** ± 1650	**1700** ± 1600	**1500** ± 1300

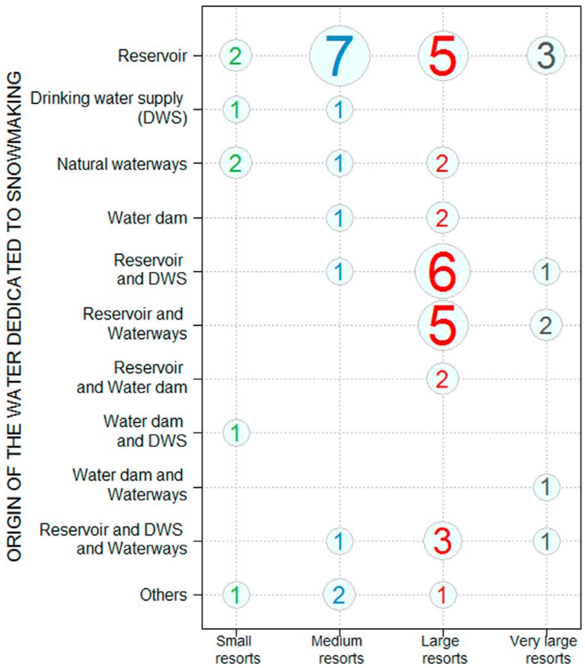

Fig. 4. Origin of the water dedicated to snowmaking. Reservoirs are defined as built exclusively to contain water for snowmaking purposes (Peyras et al., 2010) while water

pattern (data not shown): the preferred slopes depend on resorts local characteristics and stakeholders specify these slopes are "turned towards the village".

5. Discussion

5.1. Identification of influential factors for the development of snowmaking facilities

Probability of occurrence. The announced due dates for the extension of snowmaking facilities are relatively short (Table 4) regarding the planning of such projects in terms of economic investments (Damm et al., 2014), authorization processes, preliminary investigations and construction work (Peyras et al., 2011, 2010) we therefore expect such evolutions to be very likely to occur by 2020.

Vulnerability to snow conditions: a driver amongst others. Since all resorts experience contrasted natural snow conditions (Durand et al., 2009b; François et al., 2014) and pursue similar purposes (Sections 4.2 and 4.4), thus we expected the snowmaking facilities to differ between resorts with respect to their vulnerability to natural snow conditions. We compared the viability index (natural snow) from François et al. (2014) (available for French alpine resorts only) to the ratio of equipped ski slopes with snowmaking facilities. The ratio of equipped ski slopes shows a negative relationship with the viability index although it is low (slope -4.4×10^{-2}, Fig. 6) and weak (R^2=5×10^{-4}). The Pearson's product moment correlation test (Onwuegbuzie et al., 2007) confirmed the relationship was not significant (p-value=0.87). We conducted tests on subsets limited to the ski resorts of each category without significant relationship either. An additional subset was considered by excluding points when the ratio of equipped ski slopes exceeded 50% or were below 10% (Fig. 6, triangular points) consisting in 34 resorts (bullets). The slope of the linear model is −0.29 (R^2=0.15). The Pearson's product moment correlation coefficient of the sample (−0.398) is included in the 95% confidence interval (p-value=0.02) confirming a statistically significant relationship. The location of ski resorts also provides an interesting pattern: the average viability index of ski resorts are 83% and 65% in respectively the Northern and Southern Alps ski resorts (period 2001–2012) while the average ratio of equipped ski slope with snowmaking facilities are respectively 32% and 41% (Section 4.5). The analysis of the ratio of equipped ski slopes versus the vulnerability to snow conditions revealed a poor relationship although when focusing on a subset of ski resorts or on the geographical location of resorts, statistically significant reltionships were obtained. This suggests that the natural snow conditions certainly influence the development of the snowmaking facilities although this is not the only driver and may even not be the main driver.

Water supply: a discrimination factor. The average capacity of reservoirs (150–190 kg m^{-2}) allows to produce an equivalent MM snow depth over the total surface of ski slopes equipped with snowmaking facilities of 38–48 cm assuming a MM snow density of 400 kg m^{-3} (Hanzer et al., 2014), with a maximum 98 cm of MM snow depth (Section 4.5). Because of the low water availability and the high water demand due to a concentration in tourist overnight stays in winter (Lafaysse, Hingray, Etchevers, Martin, & Obled, 2011; Vanham et al., 2009), the total reservoirs volume of a given ski resort probably covers most of the total water requirements of the resort under the usual snow conditions (Vanham et al., 2007). The capacity of water reservoirs to provide the higher water demand should extend proportionnally to the surface equipped with snowmaking facilities (Section 4.5, Table 3). Beyond the financial capacity to invest, this is very likely to be a major discriminating factor between ski resorts as hypothesized by Scott and McBoyle (2007). Some resorts benefit from natural lakes or hydropower facilities which already exist (Marnezy, 2008). Other ski resorts may either heavily invest in dedicated reservoirs (where technically feasible) and/or limit the size of these reservoirs (and thus the possibility to produce snow). Some resorts may even not be able to gain access to the extra volumes of water they need for technical (Pickering, Castley, & Burtt, 2010) or environmental reasons (authorizations). The location of these reservoirs (either natural, pre existing or built for snowmaking purposes) within the ski resorts has also a significant impact on the energy consumption of snowmaking facilities: the water pressure necessary for snowmaking may be provided by the elevation difference between the reservoir and the snowguns or by additional pumping systems with overproportionally higher costs of production. On the contrary to the equal access to the energy, the access to additional volumes of water and the related inequality in costs of production therefore remain highly site dependent (Pickering et al., 2010; Scott & McBoyle, 2007).

French academic holidays: key periods. The answers of resorts stakeholders suggest they acknowledge the economic dependence to the French academic holidays as an external constraint (Section 4.4): 50% of the seasonal overnight stays is realized within the six weeks of Christmas and winter holidays altogether in Savoie Mont-Blanc[8]

Table 4
Likely snowmaking facilities in ski resorts in 2020. The surface of equipped ski slopes in 2020 was obtained by integrating results for each category (± the standard deviation). The year when the extension should be completed is a simple average of results (± the standard deviation).

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Do you plan to extend the surface equipped with snowmaking facilities? Replied "Yes" (%)	**71**	**57**	**88**	**100**
When should this be completed?	**2018** ± 2	**2020** ± 3	**2019** ± 4	**2021** ± 3
Ski slopes surface equipped with snowmaking facilities in 2020 (%)	**34** ± 32	**39** ± 17	**47** ± 46	**49** ± 38

Table 5
Priorities for the installation of snowmaking facilities in ski resorts. Average result (± the standard deviation).

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Is priority given to low-altitude areas for the installation of snowmaking facilities? Replied "Yes" (%)	**86**	**71**	**46**	**25**
Maximum altitude of snowguns (m.a.s.l)	**1450** ± 550	**1950** ± 450	**1850** ± 1100	**2300** ± 300
Is priority given to specific slopes (aspect) for the installation of snowmaking facilities? Replied "Yes" (%)	**57**	**36**	**31**	**25**
Wet-bulb temperature threshold used for snowmaking (°C)	**−3.2** ± 0.8	**−3.8** ± 0.6	**−3.7** ± 0.7	**−4.0** ± 0.8

(Lecuret et al., 2014). Such importance of academic holidays had already been outlined in Eastern North America by Scott et al. (2006) or in Sweden by Falk and Hagsten (2016).

Target customers and promotion of the resort. The development of snowmaking may be highly influenced by direct competitors either geographically or sharing the target customers. Within areas with a higher density of ski resorts, the snow guarantee may be a sales pitch to promote the resort, no matters the vulnerability to natural snow conditions. Concurrently resorts welcoming tour operators and customers staying overnight may have a stronger pressure for snow guarantee while day trippers may be more sensitive to the current snow and weather conditions (Pütz, Gallati, Kytzia, & Elsasser, 2011), may not ski on slopes limited to MM snow or pay proportionnally higher tickets prices (Riddington, Sinclair, & Milne, 2000; Töglhofer et al., 2011), leading resorts to moderate the development of their snowmaking facilities.

5.2. Framework for the analysis of the development of snowmaking and related inequalities between ski resorts

Synthesis. In accordance with previous investigations of the adaptation of the ski industry to the natural variability or projected change of the climate, our survey does not reveal highly significant differences between resorts with respect to their main features (vulnerability to snow conditions, size, location, etc.). The evolutions of snowmaking facilities in te French ski resorts are likely to remain highly individual (Trawöger, 2014) and in a large extent unplanned (Scott & McBoyle, 2007) and independent of the vulnerability to natural snow conditions (Hoffmann, Sprengel, Ziegler, Kolb, & Abegg, 2009). However, although a deterministic approach for the development of snowmaking facilities appears irrelevant, we hypothesize that several factors strongly influence the development of snowmaking facilities both at the ski slope scale (within a ski area) and at the ski resort scale (within the ski industry).

- Ensuring the spatial continuity (minimum set of skiable slopes, connections).
- Ensuring the "worst meteorological case" situation
- Promoting the ski resort by differentiating with direct competitors (international or local destinations).

Present and future inequalities between ski resorts. While climate change and variability already affect the activity of ski resorts, this survey confirms that they do not show equal capacities to face its impacts and that the gap will probably become even bigger in coming decades (Morrison & Pickering, 2013; Njoroge, 2015). The characteristics of greater adaptive capacity of ski resorts hypothesized by Scott and McBoyle (2007) are shared by the largest French ski resorts:

- The larger resorts benefit from better natural snow conditions (François et al., 2014) along with longer periods of suitable conditions to produce MM snow (Spandre et al., 2015) thanks to their higher elevation. They show lower vulnerability to snow conditions (Fig. 6) and use lower thresholds to produce MM snow (Table 5) with increased efficiencies (Marke et al., 2014).
- On one hand small resorts may not have the possibility to invest in such facilities or with questionable contribution to the viability of their operation (Falk, 2010; Pickering et al., 2010; Töglhofer et al., 2011). On the other hand large and very large resorts invest in extensive snowmaking facilities (Spandre et al., 2015) and turn it into a sales pitch towards customers (Morrison & Pickering, 2012) and into a proof of their awareness of the climate change challenges and of their anticipation of its impacts (Hopkins, 2015; Trawöger, 2014).
- Most of the largest French ski resorts (Paradiski, Espace Killy, Grand Massif, Serre Chevalier, Les Deux Alpes) belong to the Compagnie des Alpes (the largest ski lift operator in the world, Falk, 2014) or regional ski conglomerates e.g. Savoie Station Participation (Val Thorens) or Labellemontagne (Risoul, Espace Diamant), providing financial robustness
- The larger the ski resorts the more they are located in regions where skiing largely contributes to the local economy (Savoie, Northern Alps), which may facilitate the acceptation of means of adaptation by host communities.
- The willingness of customers to pay higher prices for ski lifts tickets (Damm et al., 2014; Töglhofer et al., 2011) due to the projected growing demand for MM snow production (Pons-Pons et al., 2012; Scott et al., 2003; Steiger, 2010) and rise of energy costs (Damm et al., 2014) is probably lower in smaller with respect to larger resorts (Riddington et al., 2000).
- An additional inequality related to the access to water supply remains within size categories of ski resorts or at the local scale.

At last, all findings on the behavioural adaptation of skiers to climate

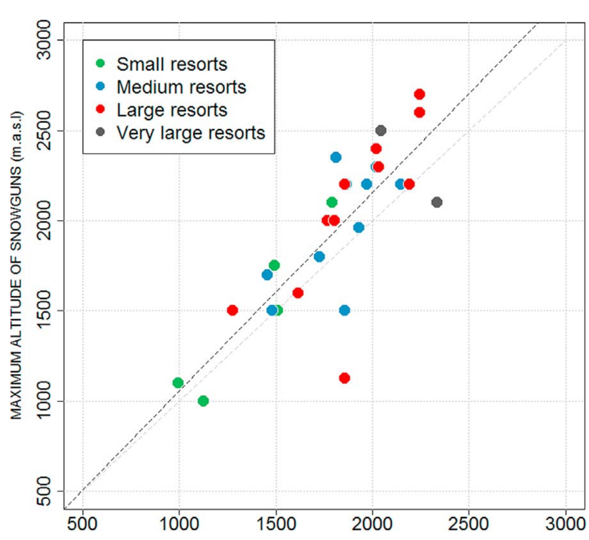

Fig. 5. The maximum altitude of snowguns (from the survey) versus the average altitude (from the "BD Stations" database) of the sample ski resorts. The dashed black line is the

[8] French departments of Savoie (73) and Haute-Savoie (74).

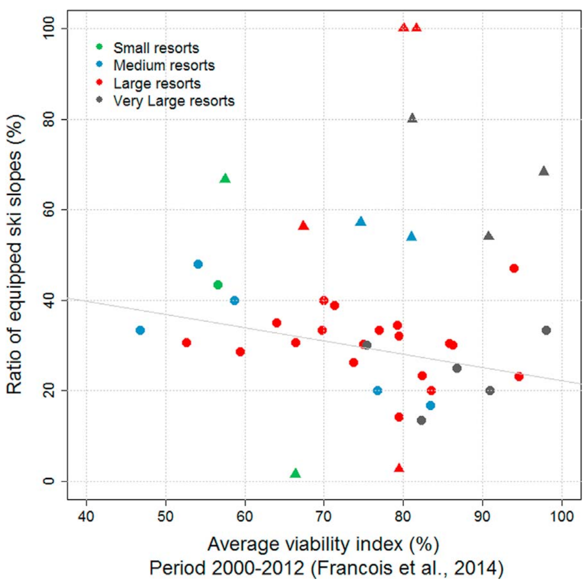

Fig. 6. Ratio of equipped ski slopes (%) versus the average viability index from François et al. (2014) for the Alpine resorts of the sample (period 2001–2012). The linear model

variability or projected changes showed that the demand for skiing activities is not likely to decrease proportionnally to the contraction of the supply (Dawson & Scott, 2013; Dawson, Havitz, & Scott, 2011; Gössling, Scott, Hall, Ceron, & Dubois, 2012; Rutty et al., 2015) and that ski resorts where skiing will remain possible will benefit from such contraction (Pickering et al., 2010; Pons, Johnson, Rosas, & Jover, 2014; Scott & McBoyle, 2007) similarly to what happened during seasons with poor snow conditions (Dawson & Scott, 2013; Falk, 2014; Koenig & Abegg, 1997). The survey therefore highlights that the competition between ski resorts is tough and is likely to increasingly disadvantage small, low to medium altitude resorts in favour of large, high altitude resorts (Marke et al., 2014; Pons et al., 2015; Scott & McBoyle, 2007; Steiger, 2010; Wolfsegger et al., 2008).

5.3. Limitations to this work

This study is subject to several limitations. Firstly the sample of ski resorts may be considered as representative of medium to very large resorts (about 50% in number and ski lift power of the national total), although a complete interview of resorts stakeholders would have improved the robustness of results. However only four small resorts participated while this is the largest category (in number) with about 130 ski resorts (DSF, 2011), hampering any generalization of the results for this category. Secondly the required snow depth for skiing activities (Section 4.4) is limited to a single value which does not account for the steepness or roughness of the ground, which is not realistic at the slope scale where erosion or accumulation by skiers may significantly modify the need for snow depth (Fauve et al., 2002). Thirdly the usual volumes of water used for snowmaking have not been explicitly required in the survey's questionnaire which is a significant shortcoming. We therefore assumed the capacity of dedicated reservoirs may cover most of the total need for water without any data to confirm this assumption.

6. Conclusion and outlooks

The present study questions the major priorities pursued by the French ski resorts stakeholders with respect to the international literature and how these drive the current practices and facilities in terms of snow management and the relevance of these relationships regarding resorts features, including their vulnerability to natural snow conditions. Our survey shows that all resorts share most operational priorities, particularly regarding the satisfaction of skiers through comfortable skiing conditions and to guarantee to ski back down to the village. Large and Very Large resorts outlined another priority which is to guarantee the connection with neighbouring resorts (if relevant), certainly related to the promotion of the resort (and associated brand) and the type of sales offer. Consistently, the required snow conditions are also very similar between the resorts categories and appear to depend more on the period of the season than on the characteristics of the resort. The minimum snow depth required in February is 60 cm on average and decreases until a minimum 40 cm in early April. A snow depth of 40–50 cm appears to be the minimum required snow depth to provide satisfying skiing conditions. As long as there is sufficient natural snow the grooming of ski slopes is an efficient method to address the suitable conditions expected by both the skiers and the ski resorts operators: over two thirds of the ski slopes are groomed every day.

In case the natural snow may not be sufficient, Medium to Very Large resorts have about 35% of their ski slopes equipped with snowmaking facilities in 2015, and almost 50% for Large and Very Large resorts by 2020 (over 30% for Medium and Small resorts). The smaller the resort the larger attention is paid to the positioning of the snowguns within the skifield (altitude, slope, aspect) with a maximum altitude for the installation of snowguns significantly related to the average altitude of the ski-lifts of the resort. In most cases ski resorts have built dedicated reservoirs to supply the water for the production of machine made snow. The capacity of these reservoirs with respect to the surface of equipped ski slopes with snowmaking facilities represents an equivalent 150–190 liters (kg) of water per m^2 (i.e. 38–48 cm of machine made snow assuming a density of 400 $kg\ m^{-3}$). On one hand the ratio of equipped ski slopes with snowmaking facilities does not show any significant relationship with the vulnerability of ski resorts to natural snow conditions although they experience contrasted conditions. On the other hand a sub sample of 34 ski resorts (by removing extreme values of the ratio of equipment) showed a significant relationship. Additionally, the analysis of resorts locations showed that the Southern Alps are the most equipped resorts at the moment (41%) and suffer a higher vulnerability to natural snow conditions (65% average viability to natural snow), at least compared to the Northern Alps (32% of equipped surface and 83% average viability), confirming that the natural snow conditions influence the level of equipment of ski resorts even though this is probably not the final decision maker but an influential factor among many others.

Such observations raise the interest for further investigations through the profiling of ski resorts, accounting for the relationship between the spatial distribution of the snowmaking facilities and both the ski lifts and real estate positioning within the ski resorts. The geographical location of a ski resort with respect to urban areas and the target market of the resort (local or even domestic versus international customers) probably influence both the flexibility of visitors, their present and future perception of snowmaking and way of consuming (through tour-operators, last minute bookings, day trippers, etc.) resulting in contrasted demands for snow guarantees and the related developments of snowmaking facilities as a prospective element. The region and department or even massif in which resorts are located certainly plays a significant role with contrasted relationships between ski resorts and host communities. Alternatively, the economic added value and the resulting capacity to invest into new facilities combined with the management mode (privately owned, semi-public or public) or the specific business model of the ski resorts might provide additional elements for the profiling of ski resorts. These two aspects may influence the final decision of investing into new facilities and the attention paid to the evolution over short to longer terms of local territories and populations, particularly regarding the potential impacts of climate change in the coming decades. Last, the density of ski resorts within a given area and the situation of each resort among its closest neighbours (size, altitude, access) may drive to the research for specificities and sales pitches (early opening, late closing, summer skiing, environment protection, car free ski resorts, etc.) resulting in contrasted development modes, particularly regarding the installation of snowmaking facilities. The observed dispersion within the category of very large ski resorts is a relevant illustration of such strategies of differentiation.

Similarly to previous investigations in Austria (Damm et al., 2014; Steiger, 2010; Töglhofer et al., 2011) or North America (Dawson & Scott, 2013; Scott & McBoyle, 2007; Scott et al., 2003) for example, the present study provides quantitative elements to model grooming and snowmaking processes in French ski resorts. This encourages and makes possible large scale modelling of the vulnerability of French ski resorts to the snow and meteorological conditions, accounting for both grooming and snowmaking impacts therefore questioning the objectivity of influential factors (vulnerability to snow conditions, investment capacity, competitors) and the relevance of indicators (defining the vulnerability) for the development of snowmaking facilities.

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Appendix A. Questionnaire

The ski resort.

- Your name and contact?
- Your resort?
- The total ski slopes surface of your resort?
- On average would you say the snow conditions in your resorts are Excellent? Very Good? Good? Fair? Weak?
- On average would you say the economic situation of your resorts is Excellent? Very Good? Good? Fair? Weak?
- On a scale from 1 (low priority) to 10 (high priority), can you address the priority of the following purposes?
  - To ensure comfortable skiing conditions for the skiers
  - To provide visually attracting slopes in the morning
  - To maintain a minimum snow depth. Please detail the snow depth required
  - To have a resistant snowpack to the erosion (by skiers, the wind, etc.)
  - To guarantee the connection with another ski resort
  - To allow to ski back down to the village
  - To reach a specific snow depth by a specific date. Please detail the snow depth and date
- Comments

Snowmaking practices.

- Is the resort equipped with snowmaking facilities?
- If not, do you plan to get equipped? When?
- The total ski slopes surface equipped with snowmaking facilities?
- Please detail the number of air/water guns in your resort? Of fan guns?
- Is the priority given to low altitude ski slopes for the installation of snowmaking facilities? If yes, please detail the altitude
- Is the priority given to ski slopes with a specific aspect for the installation of snowmaking facilities? If yes, please detail the aspect
- Do you plan to extend the ski slopes surface equipped with snowmaking facilities?
- If yes, please detail the extra surface equipped and the year when completed?
- Among the following which water supply is used in your resort for snowmaking purposes?
  - Water reservoirs. If yes, please detail the reservoirs total capacity
  - Waterways or natural lakes
  - Drinking water supply
  - Hydroelectric dam
  - Other. Please detail
- When is the snowmaking installation ready to produce machine made snow?
  - Before the 15 October
  - Between the 15 October and the 1 November
  - Between the 1 November and the 15 November
  - After the 15 November
- Which wet-bulb temperature threshold do you usually use to trigger snowmaking? −3 °C, −4 °C, −5 °C or Other? Please detail
- Do you record the water volumes used for snowmaking purposes?
- Do you intend to reduce the costs related to snowmaking?
- If yes, do you plan to optimize the amount of production? To optimize the process (investments in more efficient facilities, personnel reduction, etc.)?
- What is the main limit to the production of machine made snow in your resort?
  - The water supply
  - The energy costs
  - I stop when i do not need to produce more snow
- Once produced, do you let the machine made snow rest before grooming it? If yes, please detail how long
- Comments

Grooming practices.

- Please detail the number of grooming engines in your resort? Of groomers full time positions?
- Do you plan to invest in new grooming engines (beyond substitution)? When?
- Are the grooming engines equipped with onboard systems for the measurement of the snow depth? If not, do you plan to get equipped?
- Do you adapt the grooming schedule depending on the period of the season?
- Please detail the ratio of the ski slopes surface which is groomed every day? Every two days? Less than every two days?
- Please detail the usual grooming schedule?
- Do you intend to reduce the costs related to grooming?
- If yes, do you plan to reduce the grooming frequency? To optimize the process (investments in more efficient facilities, personnel reduction, etc.)?
- Comments

Other practices.

- Do you use snow fences in your resort? If yes, please detail the length of snow fences
- If yes, are snow fences used to reduce the erosion on ski slopes? To accumulate snow on ski slopes?
- Comments

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