Snowmaking in the French Alps: climatic context, current facilities and outlooks

P. Spandre, H. François, S. Morin, E. George-Marcelpoil

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AUTHOR'S NOTE

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Introduction

1 Winter tourism is a major driver of local economies in the French Alps. "*Ex-nihilo*" ski resorts were designed in the 1970s in French mountain regions to attract a diverse and large population. They included all the services visitors might need during their stay, from accommodation to entertainment. This new type of ski resort proved to be highly profitable; in fact, their economic revenue soon exceeded that of the industries down in the valleys (George-Marcelpoil *et al.*, 2012a). In 2013, winter tourism was a 7 billion-euro industry that employed 120,000 people (DSF, 2014). Ski lift operators ultimately bear the

responsibility for this market by ensuring access to the terrain as well as skier safety (Guily, 1991).

2 The ski resort industry experienced economic losses (Lorit (1991) and Pascal (1993)) for the first time in the late 1980s, when there were successive winters with little natural snow (Durand *et al.*, 2009b). Snowmaking seemed to be a logical way to compensate for interannual meteorological variability and the effects of climate change (Steiger *et al.*, 2008). Since then the practice has grown, with 20% of maintained ski slope areas in the French Alps equipped with snowmaking facilities in 2009 (ODIT, 2009). While snowmaking was first met with scepticism, skiers and ski lift operators alike now consider it a necessary guarantee for a skiable snowcover and, consequently, for sufficient revenue (Paccard, 2011). Snowmaking has emerged as a prominent topic as various parties weigh: (i) the economic balance between the guarantee of snow and extra investments; (ii) the natural risks related to mountain infrastructures (e.g. artificial lakes, Evette *et al.* (2011)); (iii) environmental issues (e.g. water resource management, Magnier (2013)).

3 Most European ski resorts now produce snow, although it is more common in some countries than in others. Hahn (2004) compiled existing data and found that while ~40% of Italian and Austrian ski slopes were equipped with snowmaking facilities in 2004, only ~10% of Swiss and German slopes were. However, to date, no consistent metric for calculating the proportion of equipped ski slopes has been applied; thus, the reported proportions may not be comparable between countries (Agrawala, 2007). The *Agence d'Observation, de Développement et d'Ingénierie Touristique Française* (ODIT France, the French Agency for the Observation, Development and Engineering of Tourism Activities) has not published estimations of snowmaking facilities since 2009. These six-year old estimates are the only reference for professionals (Badré *et al.*, 2009), although these facilities are constantly evolving.

4 In order to address the dearth of recent data, we have developed a robust method to assess the current and anticipated levels of snowmaking in the French Alps. In the first section, we describe our database and explain the rationale behind our categorisation (George-Marcelpoil *et al.*, 2012b). In the second section, we present a survey carried out in 2014 to investigate ski resort snowmaking facilities. In the final section, we investigate the climatic context of snowmaking by assessing the amount of time available for snowmaking over the last 50 years as a function of altitude and geographical area. We present updated and reliable information concerning current snowmaking facilities in the French Alps, drawing upon both socio-economic and physically-based models (François *et al.*, 2014).

Survey and structural data on ski resorts

Professional survey

5 In order to calculate the current and projected levels of snowmaking facilities, an online survey was set up for professionals. The *Association Nationale des Directeurs de Pistes et de la Sécurité des Stations de Sport d'Hiver* (ADSP, National Association of Ski Patrol Managers) provided 161 contacts. All these people manage technical services (grooming, snowmaking) in ski resorts in French mountain regions. An access code was allocated to every contact to guarantee personal access to the survey as well as the confidentiality of data.

The socio-economic database: *BD Stations*

6 Data from the socio-economic database *BD Stations* were used to assess the representation of the survey sample among all French Alps resorts and to process and extrapolate the survey results. The *BD Stations* database was created at the request of the *Comité de Massif Alpes*, a governing institution set up after the *Loi Montagne* law was instated in 1985. Its goal is to provide access to a wide range of data and sources focused on ski resorts through a structured framework. These data cover administrative aspects (ski lifts are part of public services and under the responsibility of municipalities) as well as economic aspects (the resort management can be handled by the municipality or transferred to semi-public or private companies). The *BD Stations* database is a powerful tool to support investigations of winter sports at different scales, from large territories where they are an activity among many others down to a single ski lift. Specific rules are applied to ski lifts, whose installation and operation are supervised by a national service (STRMTG, *Services Techniques de Remontées Mécaniques et Transports Guidés*). The STRMTG maintains a database dedicated to ski lifts (CAIRN, *CAtalogue Informatisé des Remontées Mécaniques Nationales*), which includes the technical characteristics of each ski lift such as the Ski Lift Power.

7 The Ski Lift Power (SLP) is an indicator of ski lift size commonly employed by *Domaines Skiables de France* (DSF, the French National Association of Ski Resorts). The SLP is defined as the product of the difference in height between the top and bottom of a ski lift (in km) and the number of persons that could be carried per hour (pers h^{-1}), and is thus expressed in pers km h^{-1} (DSF, 2014). When aggregated for each ski resort, it can be used to classify them into the four types described in Table 1, following François *et al.* (2014).

Table 1: Ski resort categories by ski lift power

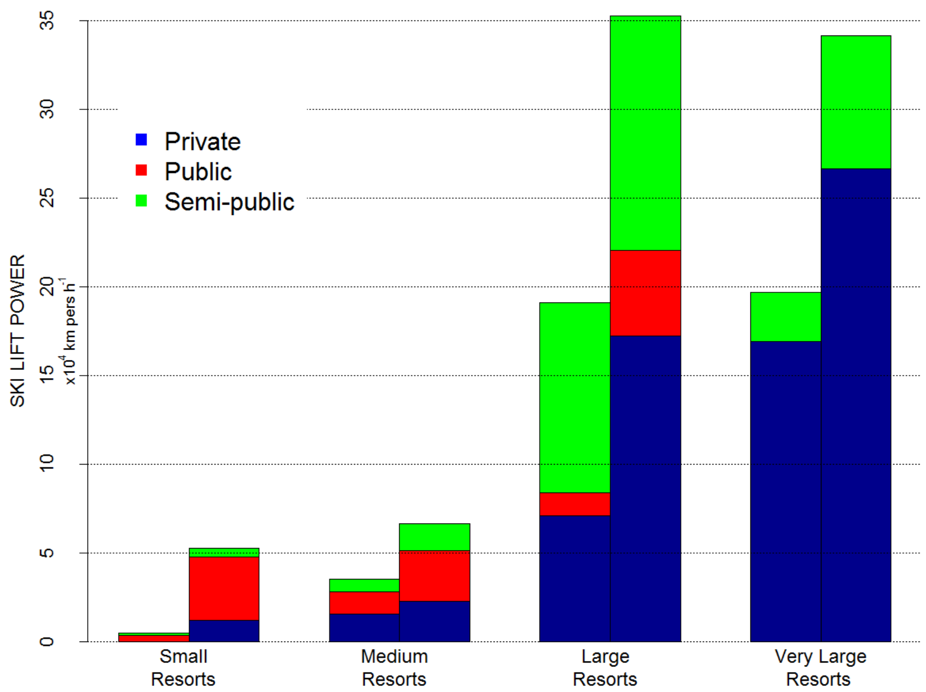
Resort category	Small Resorts (S)	Medium Resorts (M)	Large Resorts (L)	Very Large Resorts (XL)
Ski lift power (SLP, km pers h^{-1})	SLP < 2500	2500 < SLP < 5000	5000 < SLP < 15000	15000 < SLP

8 Geographical information from the BDTOPO database (25 m resolution, developed by the *Institut Géographique National*, the French Geographical Institute) can be used to delineate an estimate of skiable areas. The representations used here are "gravitational envelopes", defined as the total area accessible by the ski lifts of a resort (François *et al.* [submitted]).

Representation

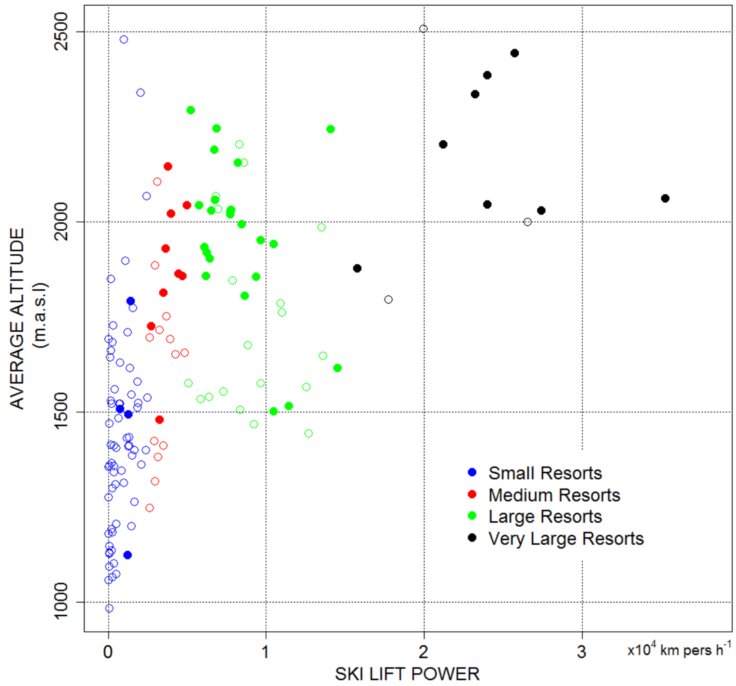
9 We presented our project on 7th October 2014, during the ADSP annual general meeting in Montpellier, Southern France. On that day, paper versions of the survey were collected from those present (18 different resorts). When the online access was closed on 9th January 2015, 56 resorts had taken part in the survey. Of these, 44 were French Alps resorts that were considered in this work, consistent with the *BD Stations* (so far, data are available only for the French Alps).

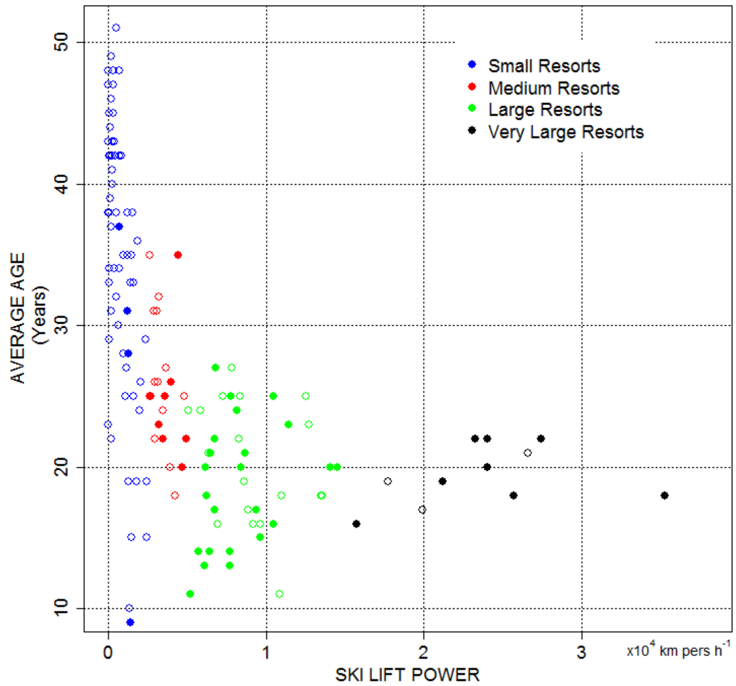
Figure 1: Ski lift power and management mode of survey sample resorts (left) and all French Alps resorts (right), by category



10 Excluding Small resorts, the survey covers 45 - 60% of the French Alps resorts for each category, in terms of both SLP and number (Appendix A and Figure 1). Overall, the sample of resorts covers 53.2% of the total French Alps SLP. Figures 1 and 2 illustrate the management mode, the average altitude and the age of the ski lifts. For each category, the dispersion of the sample is consistent with the dispersion of French Alps resorts. Consequently, Medium, Large and Very Large resort categories of the sample were assumed to be representative of the French Alps categories.

Figure 2: a) Average altitude of ski lifts and b) Average age of sample resorts (●) and other French Alps resorts (o)





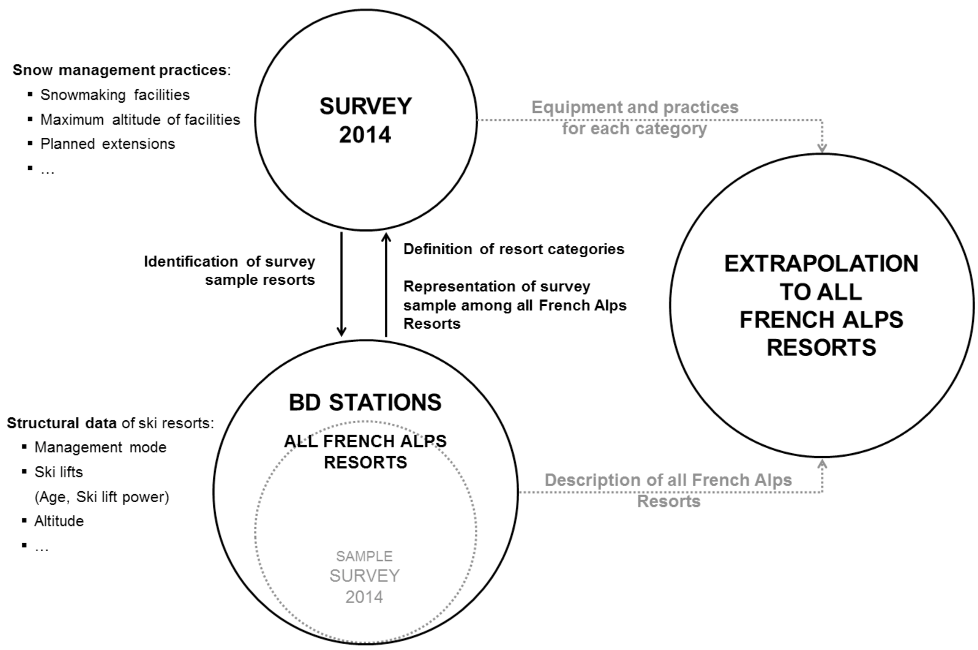
11 The survey results from the sample of S resorts were not taken into account since they did not appear representative of the S resort population in the French Alps. Instead, the S category was treated using three assumptions derived from the results of the M category.

Since the SLP of the S category is only 7% of the total SLP of French Alps resorts (Appendix A), the error it introduces into the general results appears very limited. The three assumptions used are based on François *et al.* ([submitted]), who showed that the ratio of the gravitational envelope to the SLP of a resort decreases with resort size. This ratio is twice as high for S resorts as for M resorts (0.42 vs. 0.21 ha km^{-1} $pers^{-1}$ h) while the ratio of ski slope surface area to the gravitational envelope surface area is rather constant between categories (about 10%, François *et al.* ([submitted]) and ODIT (2009)). As a result, our first assumption is that the ratio of ski slope surface area to SLP is twice as high for the S category as for the M category. Second, we assumed that the level of equipment for snowmaking facilities is more related to ski lift facilities (and thus SLP) than to ski slope surface area. Consequently, the ratio of the area equipped with snowmaking facilities to the SLP of the S category is the same as the ratio of the M category. Our third and final assumption is that the ratio of additional surface area equipped with snowmaking facilities by 2020 to SLP is half as much for the S category as for the M category. This third assumption is mostly based on the clear distinction between M, L and XL categories in terms of extension plans (Table 2 and Appendix C).

Processing and extrapolation of survey results

12 All resorts in a category were identified within the *BD Stations*, so their results were aggregated to provide an integrated SLP of the sample for the category. The *BD Stations* database also provides the total SLP of French Alps resorts for each category. The proportion of the SLP of the sample to the SLP of the total French Alps resorts was used to extrapolate the sample results for each category (Figure 3 and Appendix C).

Figure 3: Diagram illustrating the processing of the survey results using data from the BD Stations database



13 In order to assess the range of uncertainty, both low and high scenarios were considered by removing the first or last quartile of the survey sample (when resorts were ranked by their level of snowmaking facilities). This approach is equivalent to comparing the 75% most equipped resorts (higher equipment assumption) to the 75% least equipped ones (lower equipment assumption). Note that 50% of resorts are included in both scenarios. The ratio of the ski slope area to SLP was also assumed to remain constant until 2020.

Survey results: facilities growth and relationship to altitude

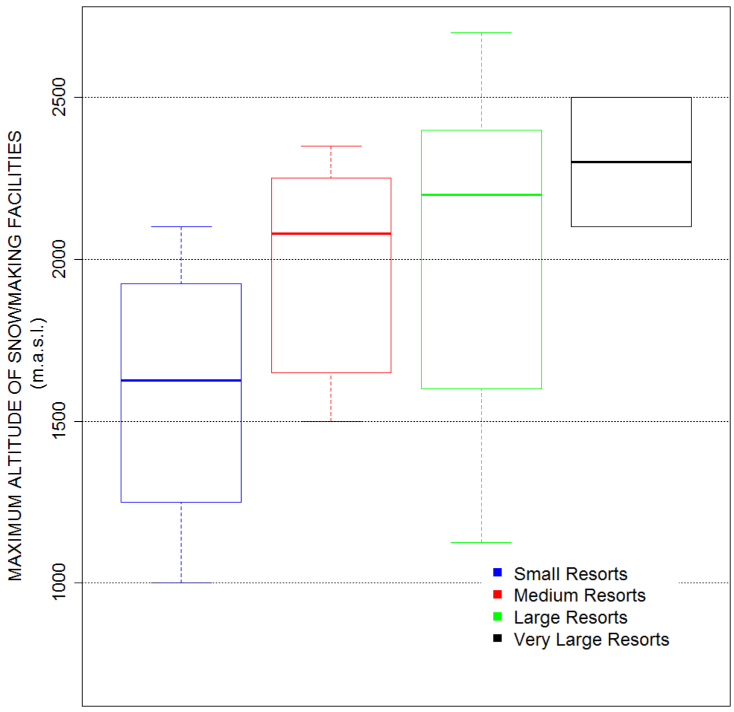
14 As shown in Table 2 and Figure 4, the facilities extensions and relationship to altitude are highly dependent on the category.

Table 2: Planned extensions and relationship to altitude of snowmaking facilities

	Small Resorts (S)	Medium Resorts (M)	Large Resorts (L)	Very Large Resorts (XL)	All Resorts
Is priority given to low altitude areas to install snowmaking facilities?	100%	100%	42%	25%	55%
Replied YES:	(4/4)	(8/8)	(10/24)	(2/8)	(24/44)
Do you plan to extend your snowmaking facilities?	50%	63%	88%	100%	82%
Replied YES:	(2/4)	(5/8)	(21/24)	(8/8)	(36/44)
When should it be completed?	2018	2020	2019	2021	2020
(Average)	[± 2 years]	[± 3 years]	[± 4 years]	[± 3 years]	[± 3 years]

15 Larger resorts give less priority to the installation of snowmaking facilities at low altitude. They also plan greater growth.

Figure 4: Maximum altitude of snowmaking facilities

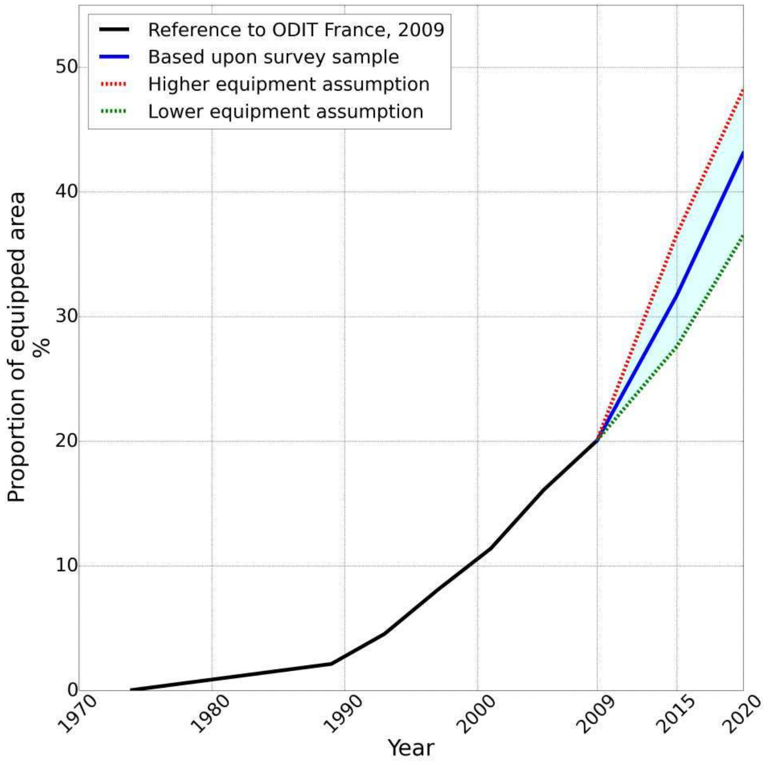


16 These results are limited to resorts that declared that they give priority to lower altitude areas for installing snowmaking facilities (Table 2). The median is shown in bold; the box includes the second and third quartile while whiskers correspond to extreme values for each category.

Survey results: estimating the proportion of the equipped surface area

17 All results are shown in Appendix C. Figure 5 also displays the extrapolated proportion of the area equipped with snowmaking facilities according to the sample results and both the higher and lower equipment assumptions. The area of ski slopes was extrapolated for each category according to methods described previously (Figure 3 and Appendix C). When aggregated over the French Alps, a total surface area of 16,500 ha of ski slopes is obtained, which is lower than the values from ODIT (2009), ranging from 19,000 to 22,500 ha. Unfortunately, the methods employed by ODIT (2009) were not disclosed (Paccard, 2011).

Figure 5: Evolution of the proportion of ski slope area equipped with snowmaking facilities in the French Alps from 1970, with projections through to 2020



THE BLUE LINE SHOWS THE SAMPLE RESULTS AND DOTTED LINES SHOW UPPER AND LOWER UNCERTAINTY BOUNDS BY REMOVING THE LOWEST AND HIGHEST QUARTILES OF THE RESULTS, RESPECTIVELY.

18 According to the survey results, the proportion of areas equipped with snowmaking facilities is 32% today. The M, L and XL resorts are similarly equipped at about 35%. However, in the next few years, they do not plan to extend their facilities at the same rate. The XL resorts will extend the existing area equipped with snowmaking facilities by 46% within 5 years, while L resorts plan a 37% increase in this area and the M resorts an 18% increase. The overall surface area equipped with snowmaking facilities should reach 43% of the total ski slope area in the French Alps in 2020. As far as we know, no prior work on the meteorological conditions suitable for snowmaking was available when these investment decisions were made. While the need for suitable conditions is expected to grow with the number of snowmaking facilities, the potential for snow production in a changing climate, and thus how much margin the resorts have to increase their facilities, is unknown. This is the subject of the third section.

Past evolution of climatic conditions suitable for snowmaking

Meteorological data

19 The *Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige* (SAFRAN) provides meteorological data (temperature, precipitation, etc.) for mountain areas referred to as "massif" (1,000 km^2 average area, Figure 6). Within each massif, the

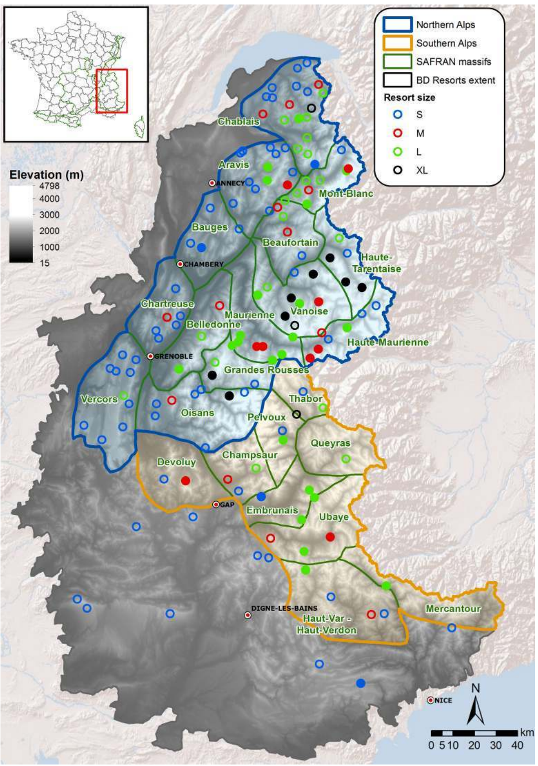
meteorological conditions are assumed to be homogeneous and to depend only on altitude (Durand *et al.*, 1993). The altitudinal step is 300 m and the time resolution is 1 h. SAFRAN combines numerical weather predictions, model outputs (large-scale atmospheric variables), surface observations (automatic weather stations, manual observations) and radiosonde observations. This data assimilation scheme has been providing information on an hourly basis since 1961 (Durand *et al.*, 2009a). However, SAFRAN is based on large-scale model reanalyses and observations that have evolved since their creation, particularly since the 1980s. This evolution is a source of inconsistency in time and space (Vidal *et al*., 2010). Despite these uncertainties, SAFRAN is a powerful tool for research purposes, which has been extensively used to assess climate change impacts in French mountain regions (e.g. Durand *et al.* (2009a), Durand *et al.* (2009b) and Lafaysse *et al.* (2011)).

Definition of snowmaking potential and the cases covered by this work

20 Snowmaking depends strongly on the meteorological conditions (e.g. air temperature, humidity, wind). The main variable used by professional snowmakers and snowgun providers is the wet-bulb temperature T_w (Olefs *et al*., 2010). The drier the air, the more T_w differs from the air temperature. All the results displayed and discussed in this work are based on $T_{w,}$ which was calculated from the air temperature and relative humidity provided by SAFRAN, following the method of Jensen *et al.* (1990). Given the current technology, snow can be produced below the wet-bulb temperature threshold of -2°C (Olefs *et al.*, 2010) although the efficiency is limited up to a threshold of -5°C (Marke *et al.*, 2014). We considered here that suitable periods for snowmaking last at least four hours (consistent with professional practices) during which the wet-bulb temperature is below a specified threshold. The snowmaking potential is defined as the summed duration of these suitable periods for snowmaking.

21 Three geographical areas were chosen by grouping SAFRAN massifs (Figure 6): the Northern Alps (14 massifs), the Southern Alps (9 massifs) and a combination of the two (French Alps, 23 massifs). Four altitude levels were also chosen: 1,200 m.a.s.l., 1,500 m.a.s.l., 1,800 m.a.s.l., 2,100 m.a.s.l. These correspond to the usual altitudes of resort villages and slopes equipped with snowmaking facilities (Table 2). They also present the most uncertainty due to lack of snow. In terms of the wet-bulb temperature threshold, -2° C was chosen as the technical limit and -5°C as the higher efficiency limit. The snowmaking potential was calculated for two distinct periods: autumn (October 1st to January 1st) and the whole winter season (October 1st to April 1st). Autumn is the period when production is greatest in ski resorts (Hanzer *et al.*, 2014); thus, any change in suitable conditions during this period will have a significant effect on snowmaking practices. However, as snowmaking occurs over the entire ski season, both periods were taken into account. The combination of all these factors (geographical area, altitude, temperature thresholds and periods of time) provided 48 distinct cases, which were processed over the 1961-2014 period. Thus, both the current state and the historical evolution of the meteorological potential for snow production could be characterised.

Figure 6: Geographical areas covered by this work, by grouping SAFRAN massifs: Northern Alps, Southern Alps and the whole French Alps, a combination of the two



THE SURVEY SAMPLE RESORTS (●) AND OTHER FRENCH ALPS RESORTS (O) ARE ALSO SHOWN BY CATEGORY.

Assessing trends

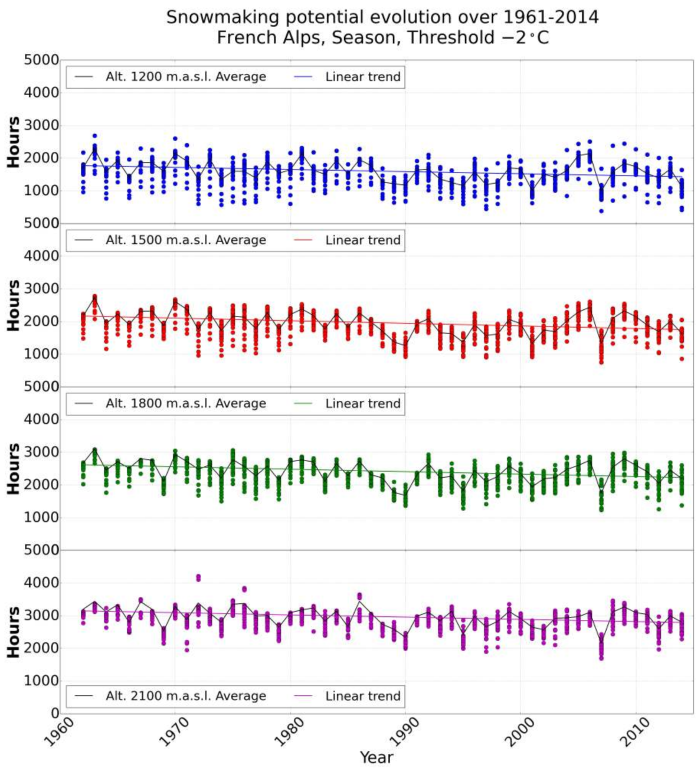
22 The analysis of SAFRAN data for each massif provided a potential for snow production that was averaged to obtain a value of snowmaking potential (in autumn or over the season) for each altitude level and for the three geographical areas: Northern Alps, Southern Alps and the whole French Alps. This method was applied for each year and altitude (Figure 7). The slope of the linear trend of the average curve and its correlation with time were calculated. In order to assess variability, the standard deviation of the average curve was also calculated. The average snowmaking potential was assessed for the decades 1961-1970 and 2005-2014. The significance level of the trend was determined using a Monte-Carlo statistical approach (Chène *et al.*, 2008), which was also used by Lesaffre *et al.* (2012) to evaluate the significance of the evolution of natural snow conditions at the Col de Porte observation site (Chartreuse, French Alps). The trend is significant if its correlation with time is higher than the correlation of a random series of the same values with time in at least 95% of cases.

Results: past evolution of snowmaking potential

23 According to our analysis of the SAFRAN data, the stronger the trend (i.e. the higher the growth rate), the higher the significance level. All twelve significant cases had negative growth rates, indicating that their snowmaking potential has decreased since 1961. For

example, at an altitude of 1,200 m.a.s.l., the seasonal snowmaking potential of the French Alps (for a threshold of -2°C) decreased at a rate of 6 hours per year (h/year) between 1961 and 2014. Other altitudes show similar rates, with snowmaking potential decreasing by 6 to 8 h/year (see Figure 7). The snowmaking potential in autumn did not present any significant trend during the 1961-2014 time period (only two significant cases out of 24), while the seasonal snowmaking potential presented many significant cases. The proportion of the potential in autumn to the potential in the whole season was 35% (for a threshold of -2°C) for the 1961-1970 decade while it was 37% (-2°C) to 34% (-5°C) for the 2005-2014 decade. The variability of the snowmaking potential in the Southern Alps is higher than in the Northern Alps: its standard deviation is 2 to 3 times greater and its correlation with time is lower. Significance levels also differ between these two geographical areas: some trends are significant in the Northern Alps but not in the Southern Alps. Most trends of the snowmaking potential in the Northern Alps are significant. Some of them are also significant for the French Alps for a threshold of -2°C, even though the trends in the Southern Alps are not significant for altitudes between 1,200 and 1,800 m.a.s.l. All the results can be found in Appendix B.

Figure 7: Snowmaking potential in the French Alps for the 1961-2014 time period



The potential over the whole season (October 1st to April 1st) is shown with a wet-bulb temperature threshold of -2°C. Each point is a SAFRAN massif; the black curve is the average of all massifs, and the coloured curve is the linear trend of the average.

24 Climate projections suggest an air temperature increase at all altitudes and for all scenarios (Lafaysse *et al.* (2014) and Castebrunet *et al.* (2014)), indicating the trends found here are likely to continue and perhaps even accelerate in the future.

Discussion

Variability and significance

25 The wide variability of the snowmaking potential is due to the variability of meteorological conditions in both space and time. First, several SAFRAN massifs in which climatic influences may differ were grouped and thus some spatial inconsistency was created. Moreover, the annual variability of meteorological conditions is well-known by mountain professionals and may be very high (Durand *et al.*, 2009b). According to our analysis, the lower the snowmaking potential, the higher the relative variability (Appendix B). As an example, the average snowmaking potential (taking all cases together) in autumn is 600 h and its variability is 72 h (i.e. 12%), while the average snowmaking potential (all cases together) in the whole season is 1,800 h and its variability is 149 h (i.e. 8%). As a result, the lower the snowmaking potential, the more likely it is that a trend could be concealed by the variability of the signal. This is particularly true for the autumn period and low altitude cases. However, the ratio of the potential in autumn to the potential during the whole season was higher for the 2005-2014 decade (34 to 37%) than for the 1961-1970 decade (32 to 35%). This may confirm that the potential in autumn did not decrease as much as the season potential did.

What is the potential for growth?

26 In 2009, 19 million cubic metres of water were used in France to produce snow on the 5,300 ha of equipped ski slopes i.e. 0.358 m^3/m^2 of ski slope (Badré *et al.*, 2009). Since three snowguns are installed per ha of equipped ski slope (national average, Badré *et al.* (2009)), every snowgun produces 1,192 m^3 of water a season. Using the usual flow of 8 m^3/h of water, the time needed is 149 h per snowgun per year. This value may appear very low compared to snowmaking potentials (Appendix B), but the margin is certainly not that large. First, production constraints are not only limited to the wet-bulb temperature, since wind speed and water availability can also reduce the potential. Air and water pumping cannot usually feed all the snowguns of a resort simultaneously (i.e. all the snowmaking facilities of a resort cannot be used at the same time). Thus, for a resort which may be able to run only a maximum of one third of its snowguns simultaneously, 450 h of production would be needed in the season. In some cases, the snowmaking potential in autumn is already as low as 450 h for a threshold of -5°C. It is very likely that some ski resorts already have to produce some snow at wet-bulb temperatures between -5°C and -2°C, and thus with lower efficiency (Marke *et al.*, 2014).

Conclusion

27 In order to describe the current and future development of snowmaking facilities in the French Alps, a survey was conducted of members of the French National Association of Ski Patrol Managers. Consistent with the *BD Stations* database, this work was limited to alpine resorts. In future work, it could be extended to other French mountain regions that are covered by the meteorological system SAFRAN but not yet by *BD Stations*.

28 Our survey showed that 32% of ski slopes are now equipped with snowmaking facilities. This proportion has increased very quickly since the 1990s and is projected to reach 40% in 2020. Even though the Medium to Very Large resorts are equipped at similar levels, their plans for extension are different. The Very Large resorts should be the most equipped resorts in 2020 (about 50% of their ski slope area), followed by the Large (48%) and Medium resorts (41%). These results confirm the differences between the capacity of resorts to adapt to the annual variability of snow conditions and climate change effects. The Very Large resorts already benefit from better natural snow conditions due to their generally higher altitude (François *et al*., 2014), which also means a greater potential to extend their snowmaking facilities (the higher the altitude, the higher the snowmaking potential). Since they plan the largest extensions between 2015 and 2020, the Very Large resorts also prove they have greater means to invest in new facilities, and thus mitigate the variability of snow conditions due to the meteorological annual variability and changes in climate (Castebrunet *et al.*, 2014).

29 Snowmaking is now thought to be the best strategy to mitigate the effects of climate change (Steiger *et al.*, 2008), but this strategy may fail. Snow production can only compensate for the lack of natural snow if several conditions are met. For example, if the early winter season experiences dry and warm meteorological conditions (such as in 2006-2007, François *et al.* (2014)) then suitable conditions for snowmaking may not be sufficient to produce the amount of snow needed (Spandre *et al.*, 2014). Our work shows that although snowmaking facilities have increased in number, snowmaking potential in the French Alps is limited and has declined since 1961. If the trends we observed continue into the future, it is likely that the need for water resources and suitable meteorological conditions for snowmaking will match or even exceed their availability. All resorts are not equally affected but all will have to face increasing costs since they will have to produce snow in less ideal conditions, with lower efficiency (Marke *et al.*, 2014). The extra profit gained through snowmaking should be balanced against the cost of such installations, given the meteorological potential for snowmaking. The development of snowmaking facilities should be limited to resorts in which the balance will be positive. Our results suggest that resorts eagerly planning the expansion of their snowmaking facilities should carefully consider the associated financial challenges and future meteorological conditions.

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ABSTRACTS

Snowmaking facilities have been commonplace in the French Alps since 1974 and particularly since the 1990s. Now, nearly all resorts are equipped with snowmaking facilities, which guarantee snow for skiers and sufficient revenue for resorts. The effects of climate change have justified recent investments in new facilities, and research efforts are beginning to combine socio-economic and physically-based approaches. We carried out a survey in autumn 2014, collecting data from a representative sample of resorts in the French Alps. We found that 32% of maintained ski slope areas in the French Alps are now equipped with snowmaking facilities; our findings indicate that this proportion is likely to reach 43% by 2020, with most of the increase in "Very Large" resorts. Although "Medium" to "Very Large" resorts are currently equipped at similar levels, the projected development varies with resort size. "Very Large" resorts are planning the largest growth, with nearly 50% of their ski slopes equipped with snowmaking facilities by 2020. However, our analysis reveals a limited potential for snowmaking in the French Alps: since the 1960s, suitable conditions have decreased by several hours per year. Since the effects of climate change are expected to increase in the coming decades (all scenarios suggest an air temperature increase), ski resorts will have to produce snow in less ideal conditions, incurring greater costs as a result of decreased production efficiency.

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Keywords: snowmaking, ski resorts, French Alps, climate change

AUTHORS

PIERRE SPANDRE

Irstea, Unité DTM, 2 Rue de la Papeterie, Grenoble, France
Météo-France - CNRS, CNRM-GAME UMR 3589, Centre d'Etudes de la Neige (CEN), Grenoble, France
pierre.spandre@irstea.fr

HUGUES FRANÇOIS

Irstea, Unité DTM, 2 Rue de la Papeterie, Grenoble, France

SAMUEL MORIN

Météo-France - CNRS, CNRM-GAME UMR 3589, Centre d'Etudes de la Neige (CEN), Grenoble, France

EMMANUELLE GEORGE-MARCELPOIL

Irstea, Unité DTM, 2 Rue de la Papeterie, Grenoble, France