Cold Regions Science and Technology 108 (2014) 98–112

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Crossing numerical simulations of snow conditions with a spatially-resolved socio-economic database of ski resorts: A proof of concept in the French Alps

H. François [a,*,1], S. Morin [b,*,1], M. Lafaysse [b], E. George-Marcelpoil [a]

[a] Irstea, UR DTM, Grenoble, France
[b] Météo-France — CNRS, CNRM-GAME UMR 3589, Centre d'Études de la Neige, Grenoble, France

ARTICLE INFO

Article history:
Received 27 May 2014
Received in revised form 16 July 2014
Accepted 22 August 2014
Available online 2 September 2014

Keywords:
Snow modeling
Ski resorts
Socio-economic
Tourism
French Alps

ABSTRACT

Snow on the ground is a critical resource for winter tourism in mountain regions and in particular ski tourism. Ski resorts are significantly vulnerable to the variability of meteorological conditions already at present and threatened by climate change in the longer term. Here we introduce an approach where detailed snowpack simulation results were crossed with a resort-level geographical and socio-economic database containing information from about 142 ski resorts spanning the entire French Alps domain. This allows us to take into account explicitly the geographical, topographical (altitude, slope and aspect) and spatial organization (distribution of ski-lifts and slopes) features of the ski resorts considered. A natural snow resort viability index was built using all the above information and simulated natural snow conditions from 2000 to 2012. Results were compared to economically relevant information (skier day values) highlighting a complex relationship between ski resort operation and natural snow conditions. The method introduced in this study holds great potential for physically-based and socio-economically-relevant analyses of the functioning of winter tourism economy and projections into the future under climate change conditions. This requires, however, that further improvements are carried out, in particular the explicit integration of snow management practices (e.g. snowmaking and grooming) into the modeling suite.

1. Introduction

Snow on the ground is a critical resource for winter tourism in mountain regions and in particular ski tourism. The ski tourism industry has continuously carried out heavy investments to maintain or improve its competitiveness (Abegg, 1996; Abegg et al., 2007; Elsasser and Bürki, 2002; Koenig and Abegg, 1997) and counteract the impact of the interannual variability of meteorological conditions (Beniston, 1997; Durand et al., 2009a). This concerns in particular snowmaking facilities, enhanced slope design and grooming practices (e.g. Fauve et al., 2008; Guily, 1991; Steiger and Mayer, 2008). Climate projections of significant temperature increase and reduction of natural snowfall amounts in the European Alps (e.g. Gobiet et al., 2014; Steger et al., 2013) and in particular in the French Alps (Lafaysse et al., 2014; Martin et al., 1994; Rousselot et al., 2012) may provide challenging environmental conditions for this economic sector. This requires us to pay close attention to the links between meteorological conditions, snow conditions and socio-economical functioning of the ski tourism industry.

In France, the building of ski resorts was closely linked to spatial planning and local development under direct governmental influence (George-Marcelpoil and François, 2012). Nowadays, the future of ski resorts is closely linked with the economy of an entire geographical area. This context has led policymakers to adopt a contractual framework to help resorts meet the challenges of the economic risks induced by meteorological variability. In contrast to North America where tourism offer is generally provided by a single enterprise in a given ski resort, ski tourism industry in French ski resorts involves a diversity of stakeholders (ski-lift companies, ski area managers, hotels, restaurants etc.) (Flagestad and Hope, 2001; Gerbaux and Marcelpoil, 2006). Public support of French ski resorts has been carried out under the assumption that the resilience of ski resorts can be improved through better organization of the tourism offer and its governance at the community level (Gerbaux, 2004; Gerbaux and Marcelpoil, 2006; Svensson et al., 2005). Due to the complexity and diversity of both mountain societies and tourism production, diversification has been funded preferentially because its enhancement reduces the dependence on snow-based business, in contrast to snowmaking facilities which have thus not been favored by public funding (Achin and George-Marcelpoil, 2013; François, 2007). From a social point of view, this approach contributes directly to the local ski system flexibility, improves its resilience (Luthe et al., 2008, 2012) and increases its capacity to overtake

* Corresponding authors.
E-mail addresses: hugues.francois@irstea.fr (H. François), samuel.morin@meteo.fr (S. Morin).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.coldregions.2014.08.005
0165-232X/

meteorologically-induced difficulties. These public policies were particularly designed for mid-altitude resorts (i.e. altitude of critical ski area lower than approximately 1500 m altitude). Facing numerous disadvantages such as their small size and the lower snow reliability than high-altitude resorts (i.e., bottom of ski resort higher than approximately 1500 m altitude), the diversification approach aims to bypass the impact of climate change. However, snow-based activities in such resorts still play a crucial role for local economy. In addition, the gap is growing between high-altitude resorts and mid-altitude resorts: on the one hand, snow remains the main resource and justifies investments in snow production equipments, while on the other hand, mid-altitude resorts currently have to deal with chronic lack of snow (Lorit, 1991; Pascal, 1993) without the help of public policies to overcome it using technical means such as snowmaking. Addressing the socio-economic component of the winter tourism economy thus requires accounting explicitly for altitude range, size, management and organizational characteristics of ski resorts, and has been attempted so far only for a limited number of case studies (see e.g. Damm et al., 2014, and references therein).

The viability of ski resorts is most often summarized by the so-called "100 day rule", which postulates that a ski resort is economically viable if snow depth above 30 cm is encountered for more than 100 days (Abegg et al., 2007). It was suggested to refine this crude rule by taking into account some structural characteristics for operating resort facilities, especially ski area organization (accounting for low and high altitude sectors) and holiday periods but also adding complexity to the 100 day rule in a multiannual perspective (Abegg, 1996; Steiger, 2010). In the latter case, a resort is considered viable if it meets at least the 100 day rule requirement 7 seasons out of 10.

While the 100 day rule has been established using natural snow depth records and may be used as such, characterizing snow conditions in ski resorts should explicitly account for the amount of snow on ski slopes. Indeed, snow management practices including grooming and snowmaking, and skier-induced erosion, exert a strong influence on snowpack properties on ski slopes with respect to surrounding natural snow areas (Fauve et al., 2008; Guily, 1991). However, many studies apply the 100 day rule using natural snow conditions, in which case the 100 day rule can be viewed as a convenient common metric to assess ski resort reliability despite its shortcomings. Numerical simulations of snow conditions can be used instead of snow depth observations allowing us to cover larger spatial extent, and open the way to long-term reanalysis of snow conditions in ski resorts and projections into the future under various climate scenarios. Several studies have attempted to address the potential viability of ski resorts on the basis of simulated natural snow depth records. For example, in the French Alps, Durand et al. (2009b) have carried out a long-term reanalysis of simulated meteorological and natural snow conditions from 1958 to 2006, and computed the average minimum snow depth which is encountered during 100 days in the same snow season, allowing us to characterize, as a function of altitude, which areas meet the 100 day rule.

Alternative modeling approaches attempt to account for technical answers to the lack of snow, more generally referred to as snow management practices. Scott et al. (2003) developed a snowmaking model they used to assess snow reliability accounting for snow production constraints. The physical part of this model is a simplified snowpack model, estimating snow cover from regional meteorological data and computing the balance between snowfall and snow melt processes. The latter was estimated using a degree-day approach. This model has progressively been refined accounting for snowmaking in an increasingly elaborated manner, while the simulation of intrinsic snowpack processes has remained relatively simple. A combination of the 100 day rule with modeling results has been used by Steiger and Mayer (2008) and Steiger (2010) to assess the future of ski resorts under different conditions of operations of a ski resort using projected climate change scenarios. These studies are partly based on previous studies by Scott et al. (2003) and Scott and McBoyle (2007). Because the snow conditions strongly depend on the regional (large scale meteorological conditions) and local (altitude range, aspect, slope) geographical characteristics of ski resorts and ski slopes, explicitly accounting for such factors is a worthwhile refinement to snow modeling studies applied to the viability of ski resorts.

Here we introduce an approach where the SAFRAN–Crocus model chain for snow on the ground numerical simulations (Durand et al., 1999; Vionnet et al., 2012) was used in combination with the "BD Stations" database, which provides resort-level geographical and socio-economic information about a total of 142 French ski resorts in the Alps (François et al., 2012; see http://www.observatoire-stations.fr). Numerical simulations carried out under a wide range of altitude, range and aspect conditions, were associated to the geographic characteristics of ski slopes within 130 French alpine ski resorts based on spatial information crossing. The method was tested for the period from 2000 to 2012. It shows the high potential of crossing meteorological and snowpack modeling with socio-economic information to produce synthetic assessments of the relationships between snow conditions and economic results of mountain ski resorts, although only natural snow conditions are considered so far in our analysis. Our work follows the logics of deeper integration of physical science and socio-economic science results allowing for transdisciplinary assessments of the relationships between these two interlinked drivers of human activities (Strasser et al., 2014). In addition, this work introduces a framework which will be expanded in the future to account explicitly for snow management techniques (including snowmaking and grooming) and allow a diversity of applications including climate projections of snow conditions in ski resorts.

2. Material and methods: integration of BD Stations and Crocus

2.1. Numerical simulation of natural snow conditions

This study uses the combination of the meteorological downscaling system SAFRAN (Durand et al., 1993, 1999, 2009a, 2009b) and the detailed snowpack model Crocus (Brun et al., 1992; Vionnet et al., 2012). In analysis mode, i.e. when surface and atmospheric observations are available for a given date, SAFRAN carries out an optimal merge of numerical weather prediction model output (large scale atmospheric fields including vertical profile of atmospheric variables), surface observations (including precipitation in mountain regions), radiosonde observations and remotely sensed cloud cover information. Surface observations consist of various sources of information. A few automated meteorological monitoring stations are located in high altitude mountain regions and measure temperature, relative humidity, wind speed and snow depth. In addition, manual meteorological observations including daily precipitation amounts, daily minimum/maximum temperature and snow board fresh snow measurements are carried out in ski resorts during their period of operation. SAFRAN is able to combine these various sources of information to provide hourly records of meteorological data needed to run the detailed snowpack model Crocus. These records depend on altitude (by steps of 300 m) within geographical zones, referred to as massifs, which have been selected because of their climatological homogeneity and are thus assumed to be meteorologically homogeneous. This means in practice that two locations at the same altitude within the same massif are assumed to encounter the same meteorological conditions. Fig. 1 shows a map of the 23 SAFRAN massifs defined for the French Alps, whose mean size is about 800 km^2. This map shows that some resorts fall outside the regions covered by the SAFRAN massifs, so that only 130 out of 142 resorts are concerned by the information crossing developed below. However, our sampling includes the most significant ski resorts in the French Alps.

The detailed snowpack model Crocus solves the surface energy and mass balance of the snowpack and features an explicit representation of snow metamorphism, snow compaction, thermal diffusion and

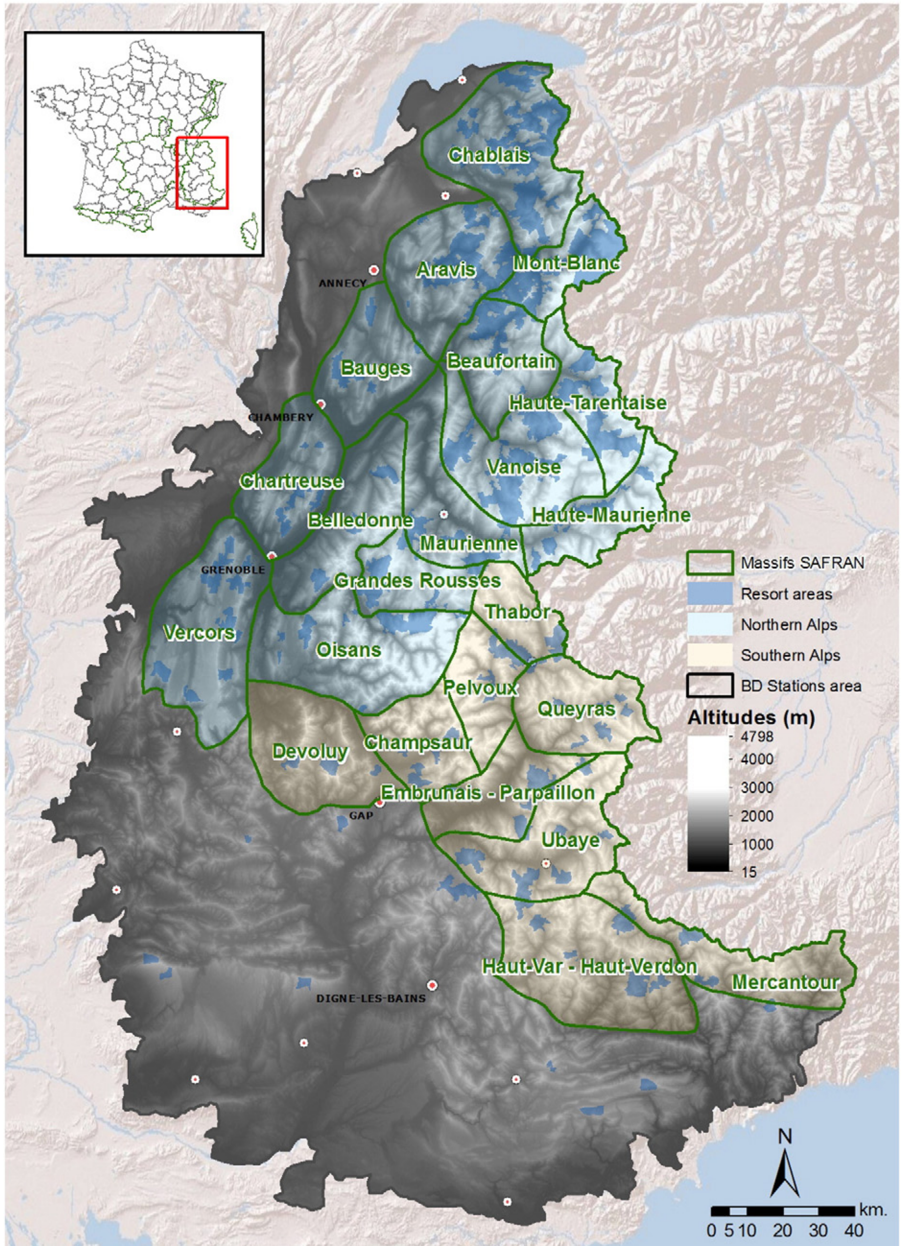

Fig. 1. Map of the French Alps. The 23 SAFRAN massifs are delineated in green. Ski areas are colored in blue. The area shaded in gray corresponds to the full spatial extent of BD Station, a fraction of it (corresponding to lowest altitude areas) is not included in any of the SAFRAN massifs. The North and South sub-domains are indicated by different colors.

water percolation both accounting for phase change effects (melt/freeze effects). At its lower boundary, Crocus is coupled to the ground component of the land surface model ISBA. Full details about Crocus, coupled to ISBA within the SURFEX modeling platform, can be found in Vionnet et al. (2012). For each massif and each altitude band, Crocus simulations can be performed using SAFRAN meteorological driving data for various slopes and aspects, in which incoming direct solar radiation fluxes are modified accordingly. In the current study, SAFRAN–Crocus simulations were performed for the entire French Alps domain spanning 23 SAFRAN massifs, by steps of 300 m altitude bands (the range of altitudes is different for each massif), for each of which Crocus model runs were carried out on flat terrain and for 8 orientations (N, NE, E, SE, S, SW, W, NW) for 10°, 20°, 30°, 40° and 50° slopes. This represents a total of 7667 idealized geographical and topographical configurations in which the model results are available. This study only considers simulated snow depth, although the model output contains much more information (snow water equivalent, surface temperature, vertical profile of the physical properties of snow including temperature, density, microstructure variables, and liquid water content; Vionnet et al., 2012). The SAFRAN–Crocus model chain is used operationally for avalanche hazard assessment and is increasingly used for alternative applications including snow hydrology, glacier mass balance, snow climatology and projections of the impact of climate change in mountain regions (Vionnet et al., 2012; see http://www.cnrm-game.fr/spip.php?article268&lang=en for an overview of known model use for research purposes). In this study, we consider SAFRAN–Crocus results as representative for the natural snow conditions encountered in the French Alps for the time period from 2000 to 2012. Indeed, a recent evaluation of the performance of the SAFRAN–Crocus model chain in terms of snow depth has been carried out using observations from 83 daily and weekly snow depth monitoring stations in the French Alps over a period of 32 years (1980–2012). The mean bias was found to be 4 cm and 0 cm for daily and weekly observing stations, respectively, and the root mean square deviation was found to be 26 and 43 cm, respectively (Lafaysse et al., 2013). Such values, representative of the performance of the combined system SAFRAN and Crocus against in-situ snow depth measurements, correspond to the typical level of performance of point-scale snowpack models driven by in-situ meteorological conditions (e.g. Essery et al., 2013) and indicate that using SAFRAN–Crocus results is appropriate for this study.

2.2. Spatial representation of ski slopes and ski-lift power distribution in ski resorts

For an integrated joint analysis of socio-economic and snow conditions for a series of entire ski resorts, it is crucial to aggregate physical and socio-economic results at least at the level of each ski resort. This requires us to give different weights to each ski slope within each resort taking into account the geographic structure of ski-lift distributions and the topographic characteristics of the ski resort (combined influence of aspect, slope and altitude). Along this line, Steiger (2010) considered ski areas as divided in lower and upper areas, and gave more weight in the viability analysis to the upper one. In order to fully assess ski resort operations i.e. to accurately combine snow conditions, ski slope and ski-lift characteristics, one would need a comprehensive knowledge of the spatial organization of ski-lift and ski slopes within each resort.

The BD Stations database contains some of the required spatial information and attribute data about ski resorts (François et al., 2012). Geographic data for ski slopes is only available for a small subset of resorts (e.g. OpenStreetMap project, see below). Moreover, this level of precision would not be consistent with other datasets used in our work, and the fact that ski slope configurations change from year to year would add a level of complexity to our analysis which is not possible to address with current means. In terms of ski-lifts, beside their location on the IGN (Institut national de l'information géographique et forestière — French Geographical Institute) 1:25,000 map, the only quantitative information available to us through “Ski-lift data base” (referred to as FIRM, standing for Fichier Informatisé des Remontées Mécaniques, provided by Service Technique des Remontées Mécaniques et des Transports Guidés — STRMTG), is the bottom and top altitude of each ski-lift and the corresponding ski-lift power, expressed in persons unit elevation difference per hour (thus expressed in persons km h^{-1}). Ski-lift power data aggregated for each ski resort allow us to classify them in four resort types, referred to as small (S), medium (M), large (L) and very large (XL) depending on their total ski-lift power values below 2500 persons km h^{-1}, between 2500 and 5000 persons km h^{-1}, between 5000 and 15,000 persons km h^{-1}, and above 15,000 persons km h^{-1}, respectively. This classification is identical to the ski resort classification used by Domaines Skiables de France (DSF, the French union of ski-lift managers and manufacturers). Fig. 2 shows the distribution in terms of number of resorts and ski-lift power of the 130 ski resorts considered in this study. It indicates that, while L and XL resorts make up only 43% of the total number of resorts, they contribute 86% of the total ski-lift power. In contrast, S and M resorts comprise more than half of resorts but only 14% of total ski-lift power.

Our geographical analysis of ski resort spatial organization is based on the digital elevation model (DEM) BDTopo from IGN which describes terrain elevation as 25 m pixels, on the IGN map of ski-lifts, and on the FIRM data (note that the latter two are unfortunately not cross-linked).

- Geographical assessment of potential ski slopes
  The geographic location of ski-lifts can be used to infer a reasonable estimate of geographical characteristics of ski areas, assuming that ski slopes are generally located in the immediate vicinity of ski-lifts with few exceptions. We believe that this approach provides a reasonable estimate of potential ski slope location and geographic characteristics. To do so, a polygon of potential ski slopes was built in three steps for each resort. Fig. 3 shows the different steps of this geographical analysis of ski-lifts for a given ski resort (Fig. 3a). Firstly, we applied a positive buffer on ski-lift ground footprint (Fig. 3b) and merged the resulting geometries to make a single polygon which was the basis for applying a negative buffer slightly smaller than the positive one (Fig. 3c). With this method we obtained a continuous envelope for each ski resort.

- Elevation slices of ski-lift envelopes
  The elevation range of each ski-lift and the associated potential ski slope polygon was the first factor we took into account to match the geometry of SAFRAN–Crocus output. Ski-lift envelopes were divided into 300 m slices, using information from the DEM (see Fig. 4). In this particular example, the ski slope map from the OpenStreetMap project is available and confirms that most ski slopes are captured by our analysis. Indeed, in this case, only one very difficult ski slope (black level) is missed.

- Ski-lift power repartition between altitude slices
  The representation of the spatial organization of the ski resort has to take into account the location of ski-lifts together with their corresponding ski-lift power. In order to do so, we considered ski-lifts as vertical lines intersecting at different elevation slices by steps of 300 m between their bottom and top altitudes. SAFRAN–Crocus results represent snow cover +/− 150 m from a given altitude level (for example, the altitude 1200 m corresponds to simulated snowpack conditions between 1050 and 1350 m). Thus, a ski-lift between 900 m and 1500 m has 25% of its power assigned to the 900 m slice (750–1050 m), 50% assigned to 1200 m slice and the last 25% assigned to 1500 m (1350–1650 m). This means that we ignore the fact that the ski-lift ground footprint may be different from the simple altitude range covered within each elevation slice. Deviations can be encountered if the terrain slope varies greatly from the bottom to the top of the ski-lift, but we anticipate this effect to be negligible against the other assumptions made in our study.
  Each ski resort is linked to one SAFRAN massif, and within the resort

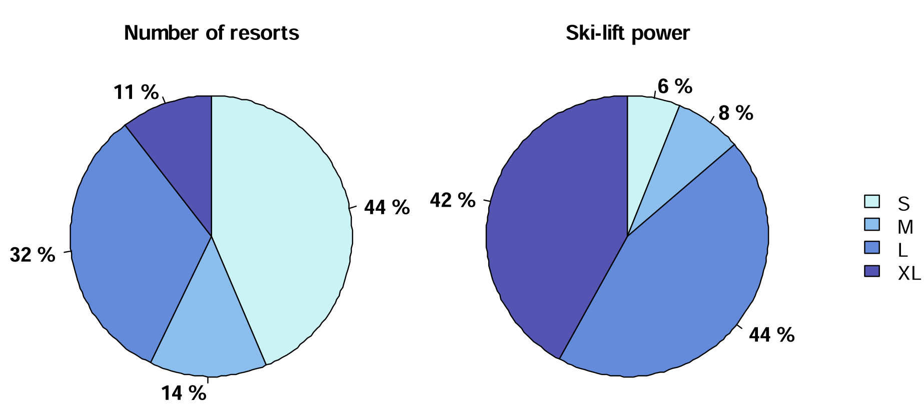

Fig. 2. Distribution of ski resort classes (S, M, L, and XL) in terms of number of resorts (left) and ski-lift power (right).

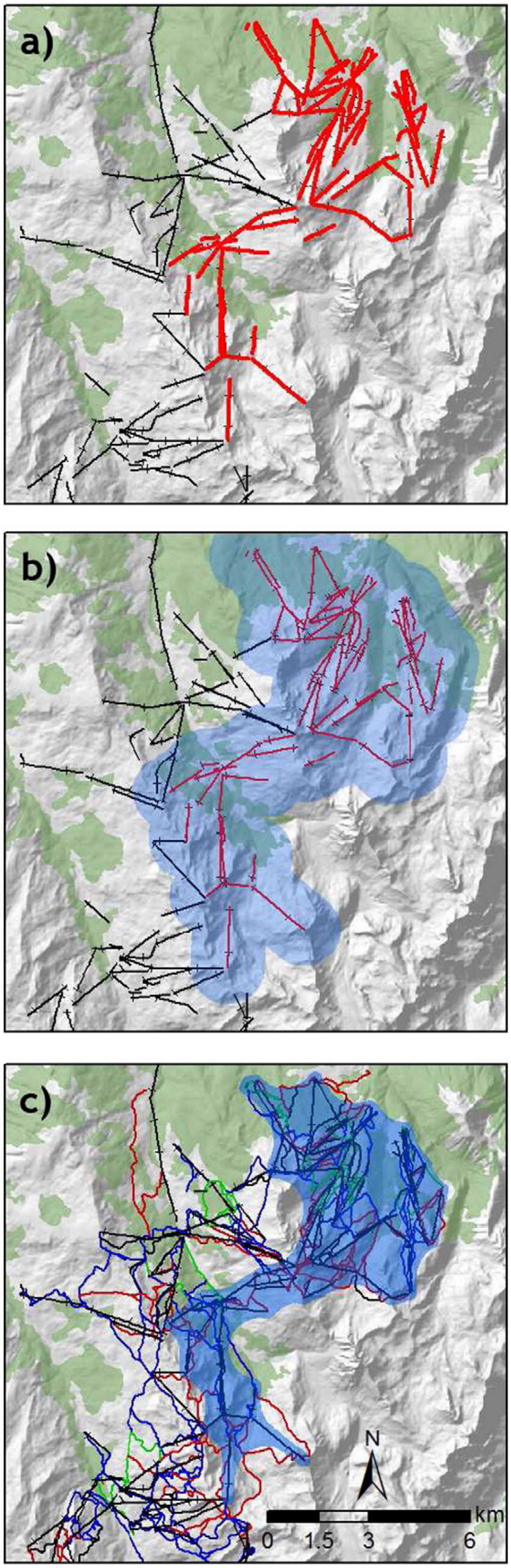

Fig. 3. Overview of the steps conducive to the estimation of ski slopes envelopes. a: Overview of the starting material: and identification of ski-lifts corresponding to a given resort. b: Positive buffer leading to continuous oversized ski area. c: Negative buffer maintaining connectivity of the ski area within a given ski resort.

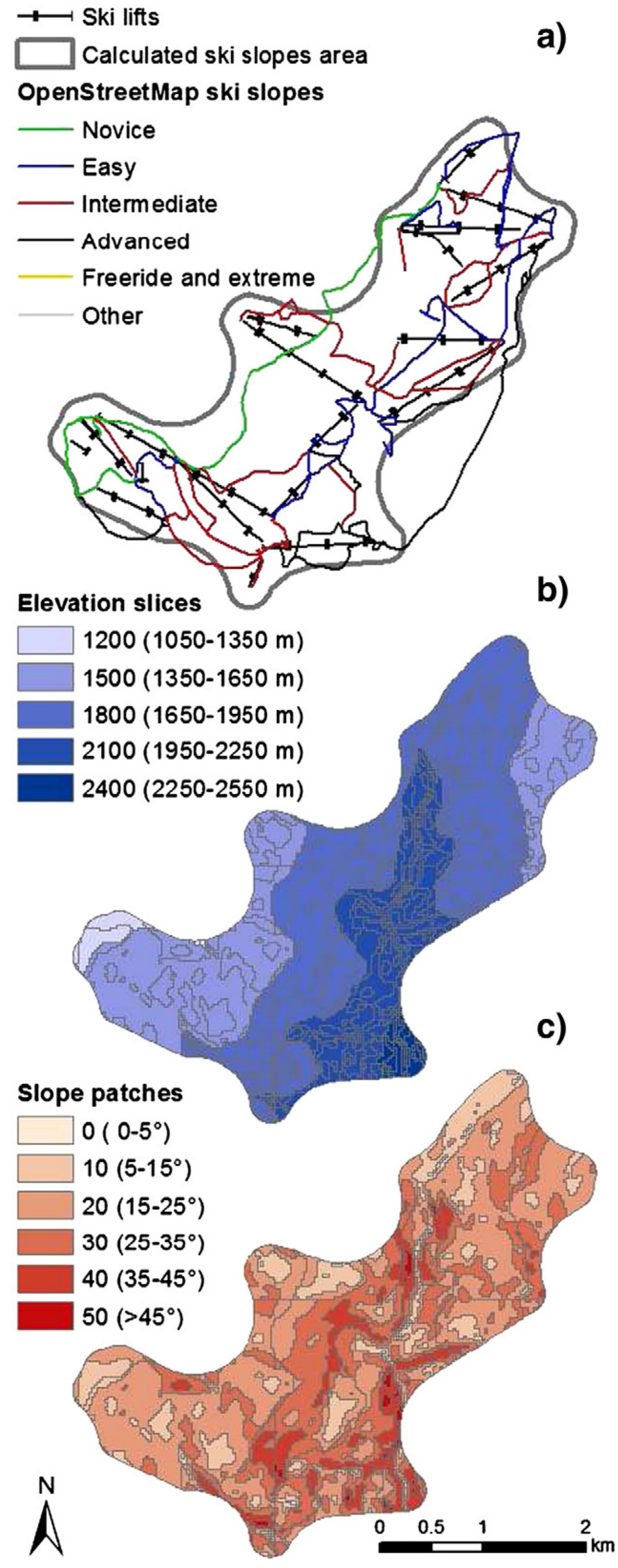

Fig. 4. Comparison of the estimation of ski areas for a given resort (Les Sept Laux, near Grenoble) based on ski-lift envelopes with OpenStreetMap ski slopes (a) and examples of elevation slices (b) and slope slices (c).

the sum of ski-lift power within each altitude slice is attributed to this altitude slice. In the case where a resort intersects with several massifs, it has been decided to fully assign it to the massif for which the envelope area intersection is the larger. Table 1 shows a list of all ski resorts considered in this study with their corresponding SAFRAN massif, lower/higher altitude range, and total ski-lift power.

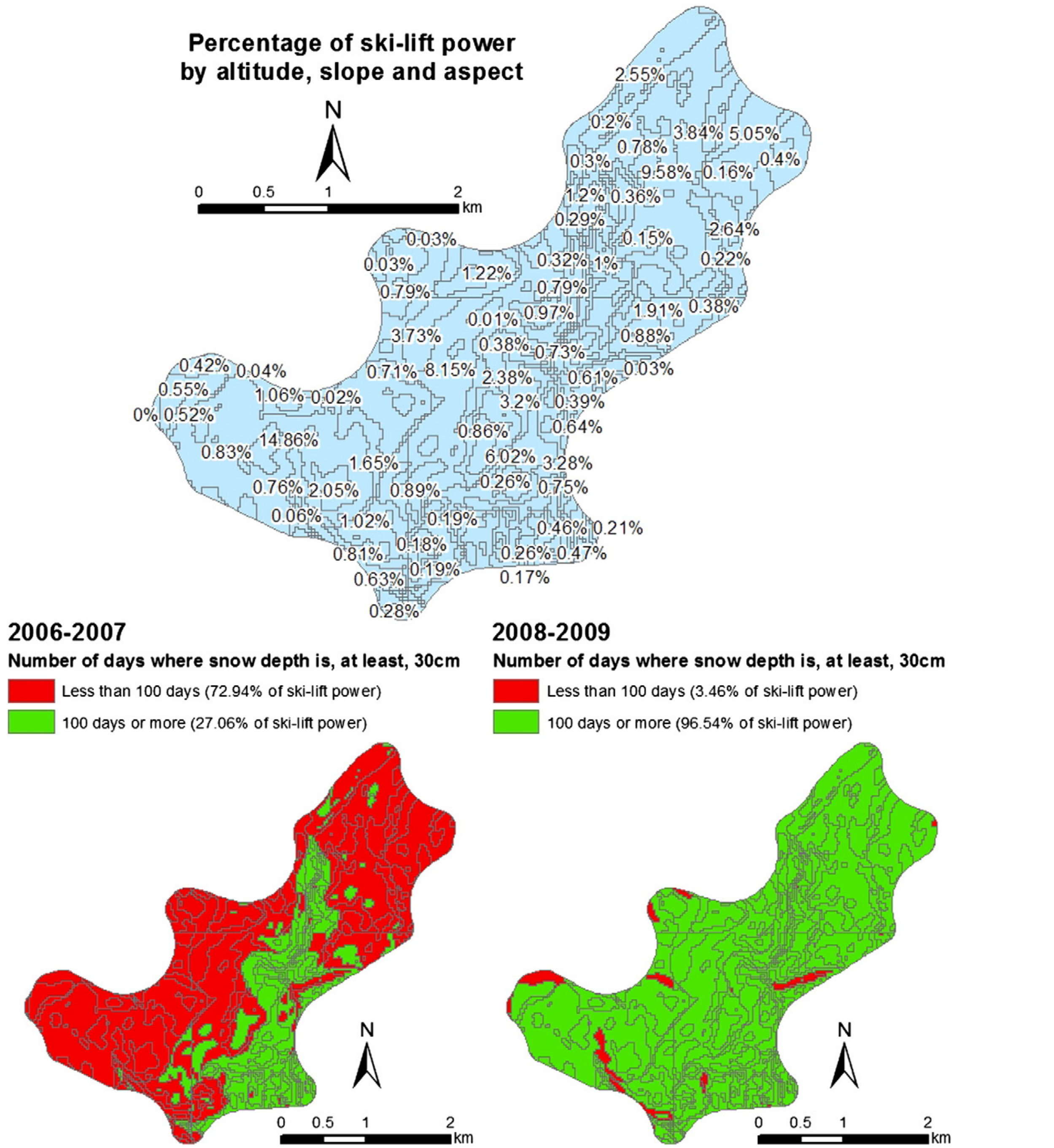

Fig. 5. Illustration for a given resort (Les Sept Laux, near Grenoble; same as Fig. 4) of the percentage of ski-lift power shared by the altitude, slope and aspect patches used to discretize the total surface area of each ski resort (top), and example of the application of the fractional 100 day rule for the snow seasons 2006–2007 (bottom left) and 2008–2009 (bottom right).

• Slopes and aspect considerations
The first step, described above, was meant to distribute ski-lift power between elevation slices. Each elevation slice was then divided into several slope patches on the basis of the actual slope from the DEM. Each pixel of the DEM was linked to a slope class corresponding to the nearest value in terms of SAFRAN–Crocus class discretization (less than 5° linked to flat configuration, between 5° and 15° linked to 10° etc.). Contiguous pixels belonging to the same slope class were grouped together and are referred to as patches. For each patch, an average aspect was computed. Finally each pixel of the DEM within the ski resort envelope can be linked to SAFRAN–Crocus results, organized as a function of altitude slices, slope and orientation. Ski-lift power within a given elevation slice was then distributed between slope and aspect classes within the same elevation slice on the basis of their respective slope-parallel surface areas. Ultimately, each pixel of the DEM within the envelope of the ski resort corresponds to a specific fraction of the total ski-lift power in a manner which is computationally efficient. This fraction was used to weigh the results of SAFRAN–Crocus simulations associated to each pixel, to provide an integrated assessment of snow conditions accounting for the altitude, the ski-lift power partitioning in a ski resort and the topographic characteristics of the ski resort.

2.3. Computation of an integrated snow reliability index for ski resorts

For each pixel in the DEM we use the record of daily snow depth data from SAFRAN–Crocus to compute a pixel-based binary indication for each season. For each pixel, a value of 1 is assigned if it meets the

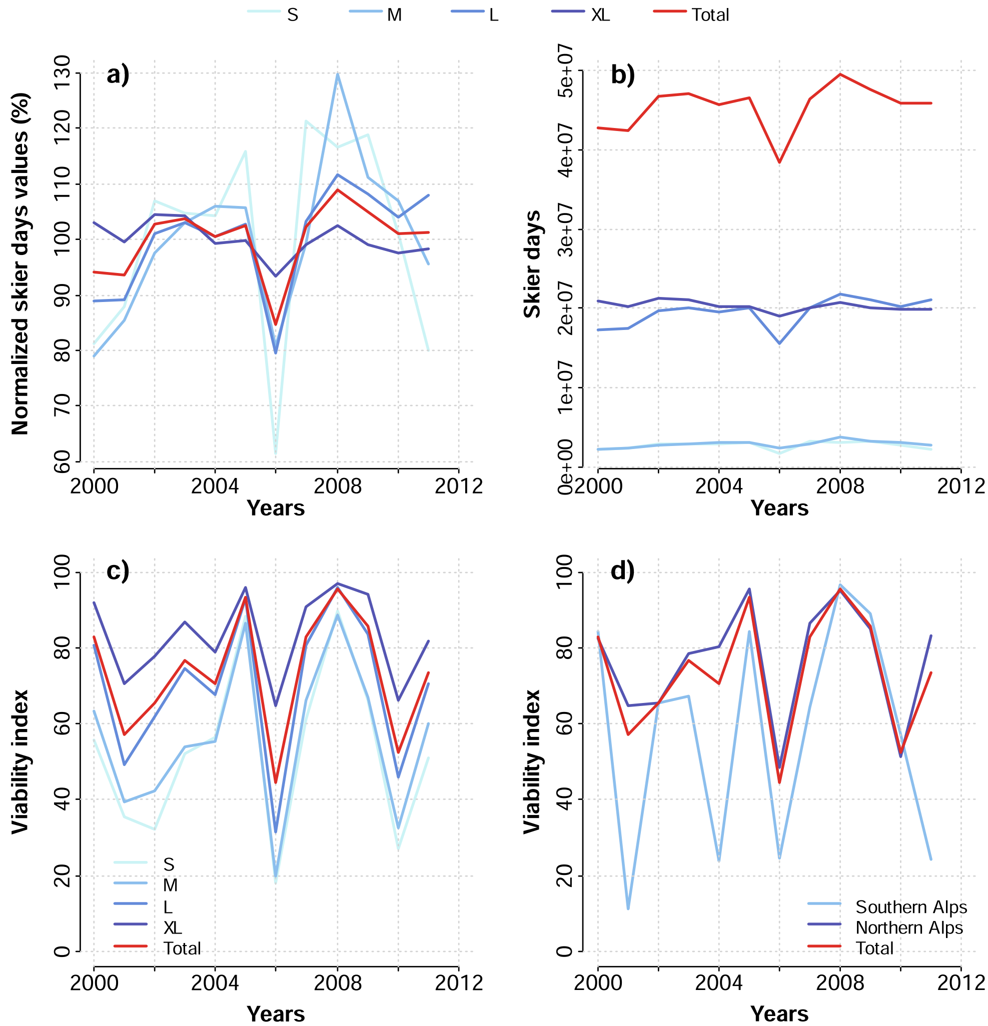

Fig. 6. Time evolution from the seasons 2000–2001 to 2011–2012 of the snow season skier day values (a) with respect to 2000–2012 mean and (b) absolute as a function of ski resort class and the viability index (based on natural snow conditions) (c) as a function of ski resort class and (d) separating Southern and Northern French Alps domains. For each year, the label corresponds to the first half of the winter season (i.e., 2000 corresponds to 2000–2001).

100 day rule, 0 otherwise. Here we considered the 100 day rule in its most basic formulation, i.e. we simply counted the number of days in which snow depth exceeds a 30 cm threshold within a given snow season (i.e. from 1 August to 31 July). The pixel-based binary information was then aggregated at the resort level using the ski-lift power fraction associated to each pixel. The obtained number, for each snow season and each resort, can be viewed as the fractional viability of the ski resort, ranging from 0% to 100%. Fig. 5 shows an example of how this index is calculated, for the same ski resort displayed in Fig. 4 and for the snow seasons 2006–2007 and 2008–2009.

2.4. Socio-economic data from ski resorts

To complement the integration of BD Stations and SAFRAN–Crocus results, the viability assessment was put into the perspective of economic results. In this field, BD Stations include data collected and provided by DSF: business turnover, winter revenues and number of skier-days during the season. Some of these data are better adapted than others to be used in our study. The first one does not only reflect the activity during the season but also the investment dynamics which also depends on the resort size. Given the inequalities between resorts, it is very difficult to deal with this variable quantitatively. Winter revenues are also difficult to compare between resorts. As they play the role of competitive lever, they are directly involved in the management strategy to respond to snow conditions during the snow season and ski resort location or local competition (especially as a function of distance from main cities). In contrast, skier-days directly measure the number of different persons who bought a ski-lift ticket for the day. It is the unit used to compare tourist traffic between resorts. Another limit has to be considered when we use socio-economic data because they are collected on a declarative basis, thus the choice to send data to DSF depends on the willingness of the ski-lift operator. This one is clearly linked to the season economics: it is always easier to communicate results when they are good. However, this dataset is the only possible way to address socio-economic functioning of ski resorts. Indeed, the diversity of status of ski-lift operators (public, semi-public or private) induces a large spread of accounting frameworks and legal obligations, so that it is virtually impossible to gather the information required from official reports. Moreover, DSF data rely on ski-lift management companies (several can co-exist within the same ski resort), which is consistent with the organization of the BD Stations. 105 resorts have provided sufficiently detailed skier day information so that their data can be used in the following analysis. In case of missing data for a particular snow season in a given resort, we carried out time interpolation using growth rate from resorts belonging to the same class (S, M, L and XL). This concerns, for example, 57.14% (60/105) for 2006–2007 and 43.81% (46/105) for 2008–2009.

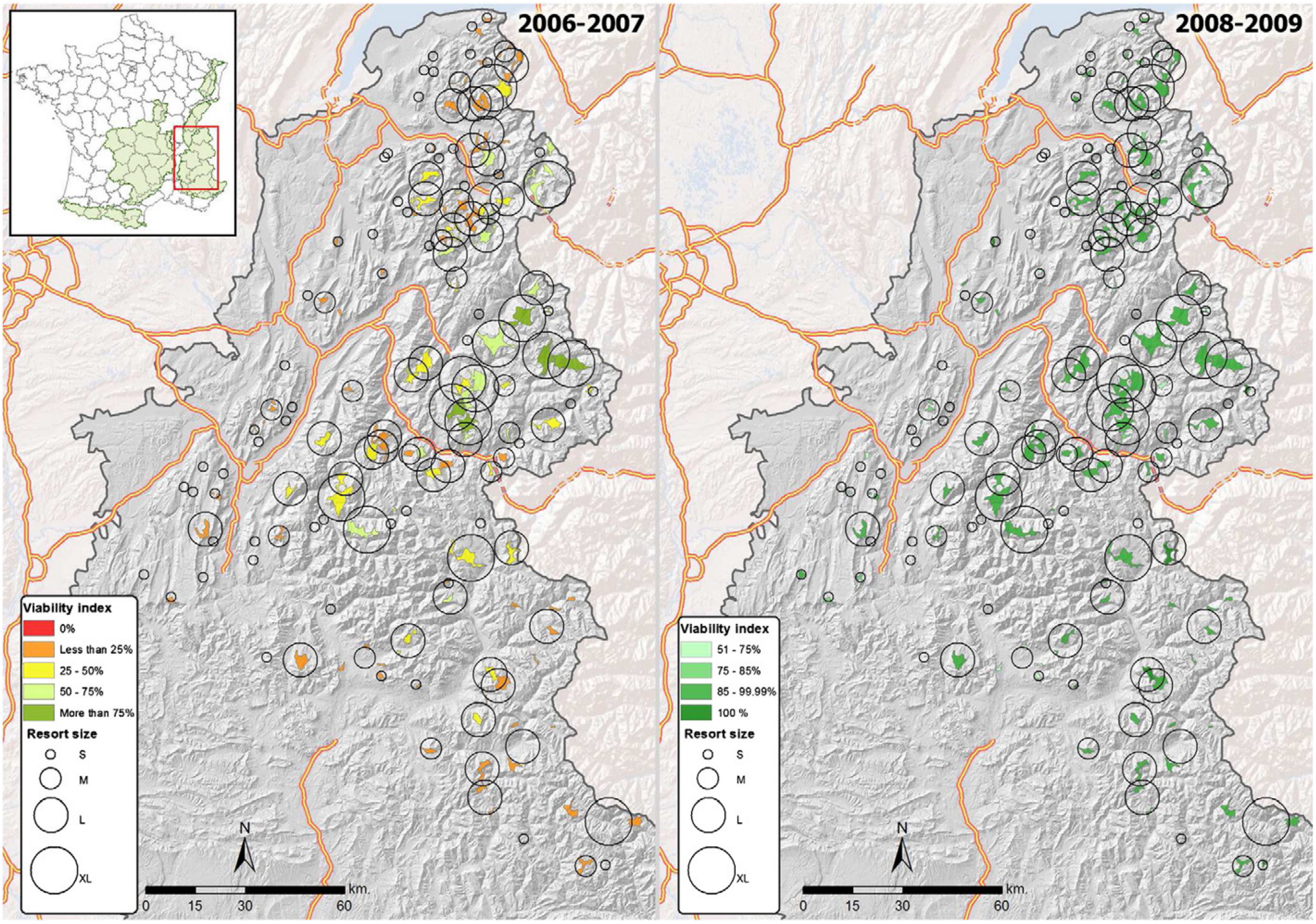

Fig. 7. Map of the geographical location of ski resorts with a color code corresponding to the viability index in 2006–2007 (left) and 2008–2009 (right) and resort classes. Note that the color bar is different between left and right but remains consistent for a direct comparison of the two maps.

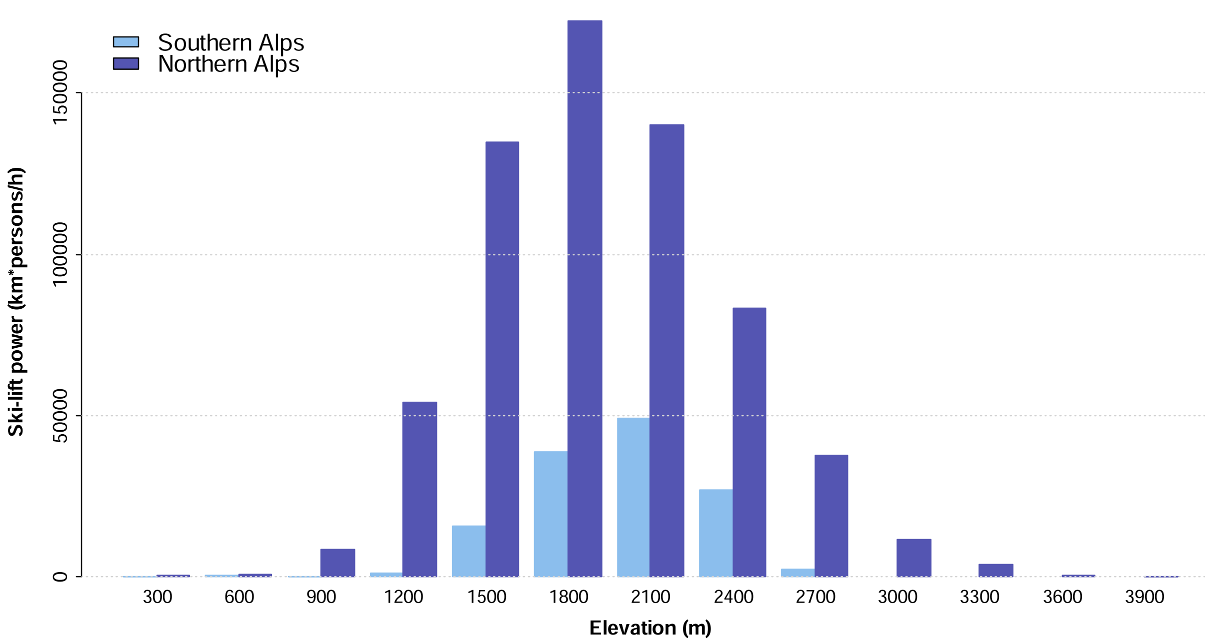

Fig. 8. Altitudinal distribution of ski-lift power in the Southern (light blue) and Northern (dark blue) French Alps in 2012–2013. Each altitude indicated in the x-range is the center of a 300 m wide altitude range.

3. Results and discussion

The following results are based on numerical simulations of natural snow conditions in the French Alps, using the SAFRAN–Crocus modeling suite, and the BD Stations database. Results purely related to resort geographic characteristics stem from the full list of the 142 resorts included in BD Stations. Viability indices, derived from the crossing of SAFRAN–Crocus and BD Stations, are computed for the 130 resorts included in the 23 SAFRAN massifs. The socio-economic analysis is restrained to a subset of 105 resorts which have provided usable skier day values and are located in the 23 SAFRAN massifs.

3.1. Natural snow conditions and operations of ski-lift facilities

Fig. 6 shows the time evolution from the seasons 2000–2001 to 2011–2012 of (a) relative skier day values with respect to the 2010–2012 mean within each ski resort class and (b) absolute skier day values as a function of ski resort class (S, M, L, XL and total) and the viability index based on natural snow conditions (c) as a function of ski resort class and (d) separating Southern and Northern French Alps domains. Fig. 6c clearly illustrates the larger interannual variability of snow conditions in small resorts (from 18 to 90% for S resorts) than in larger resorts (e.g. from 65 to 97% for XL resorts). This difference is mostly explained by the altitudinal distribution of ski slopes, since ski-lift power of smaller resorts is generally located at lower altitudes than larger resorts. S and M resorts feature viability levels more often below 50% than the L and XL resorts. Overall, the snow seasons 2006–2007 and 2010–2011 stand out as the worst snow seasons of the past decade in terms of natural snow conditions, even for high altitude resorts. Focusing on S and M resorts, the snow seasons 2001–2002 and 2002–2003 are also below 50%.

Fig. 6d shows that snow conditions in ski resorts in the Southern Alps exhibit much larger year-to-year variations than in the Northern Alps, regardless of the resort type (data not shown). In 2006–2007, the snow conditions were significantly lower than average both in the Northern and Southern Alps; in 2008–2009, the snow conditions were significantly better than average in the Northern and Southern Alps. In contrast, the snow season 2010–2011 was worse with respect to average in the Northern Alps than in the Southern Alps. Lastly, the snow season 2011–2012 shows good viability conditions in the Northern Alps (83%) but significantly bad conditions in the Southern Alps (24%).

The evolution of skier day values shows distinct patterns depending on the size of the resorts (Fig. 6a and b). Overall, the snow season 2006–2007 was the worst in terms of skier days during the whole time period while the snow season 2008–2009 was the best. 2008–2009 is also known to be the first season when France became the world's primary skiing destination (in terms of skier days). Skier day values in XL resorts do no show significant variations, except a relatively steady decline totalling about 5% over the time period considered. L and S resorts show significant relative reductions during the season 2006–2007, but they also show a significant relative increase during the season 2008–2009 (Fig. 6a). Lastly, M resorts show a peculiar behavior. After a regular growth of skier-day number, the 2006–2007 ski season decline was relatively small. During the 2008–2009 season, they showed a higher relative growth. In short, over the time period studied, in terms of skier days:

- XL resorts seem to be rather insensitive to interannual variations of meteorological and natural snow conditions,
- L and S resorts react strongly both to exceptionally unfavorable and favorable environmental conditions,
- M resorts are more positively affected by favorable environmental conditions than negatively affected by unfavorable environmental conditions.

Interestingly, the 2006–2007 season was both unfavorable in terms of snow conditions and skier days, while the 2010–2011 season was unfavorable in terms of snow conditions but did not show the same drop of skier days than that in 2006–2007. Additional effects than natural snow conditions are clearly needed to understand this pattern. However, the current status of our modeling platform does not allow us to delve deeper

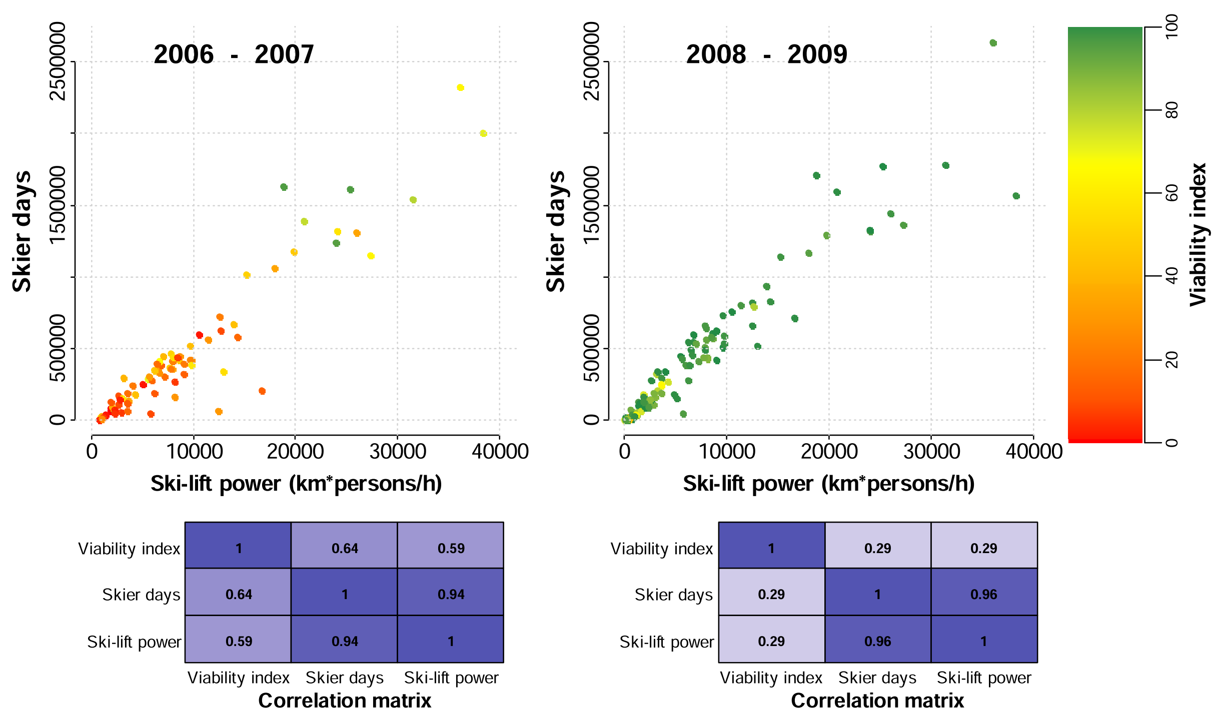

Fig. 9. Scatter plot between skier day values for 2006–2007 (left) and 2008–2009 (right) and ski-lift power (one point per ski resort). The color code indicates the resort-level viability index, based on the natural snow conditions and ski resort geographical and ski-lift power altitude distribution characteristics. Below the plots are given correlation tables between the viability index, skier day values, and ski-lift power, for each of the two seasons considered.

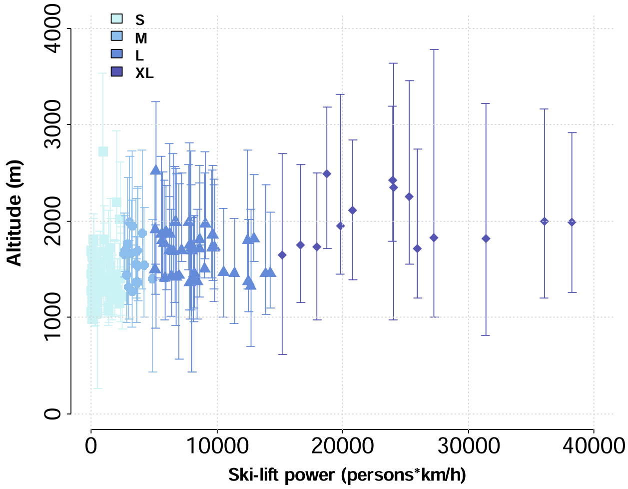

Fig. 10. Scatter plot between resort-level total ski-lift power and lower, higher (tips of the vertical bars) and ski-lift power-weighted mean altitude (symbols). Different symbols and colors correspond to the ski resort classes.

into the understanding of these observations. Conversely, these findings illustrate that snow management practices should be fully taken into account to understand the links between meteorological conditions and the socio-economic functioning of the winter tourism industry.

In the following, we focus on the two extreme seasons 2006–2007 and 2008–2009. For professionals of the sector, it is commonly admitted that the poor skiing conditions in resorts during the 2006–2007 season could be explained by a warm winter which limited the possibility to carry out snowmaking, in addition to insufficient natural snowfall (e.g. Luterbacher et al., 2007). Fig. 7 shows the results from the snow reliability index for each resort for the snow seasons 2006–2007 and 2008–2009, along with ski resort size, and clearly illustrates the contrast between the two seasons studied. During the 2008–2009 ski season, no resort has known to have a viability indicator lower than 50% which is consistent with the good economic results in terms of number of skier-days. The maps also show that the heart of the alpine region considered, on the eastern side, is less impacted. This difference between resorts can be traced to their elevation. This spatial distribution follows that of the topography and underlines an east–west gradient, from the borders to the heart of the Alps. It suggests the primary role of altitude to explain economic results.

3.2. Inequalities between regions and resorts

The spatial and altitudinal distribution of ski resorts has to be discussed regarding resort building in the French spatial development policy referred to as the "*Plan neige*". That policy implied a strong public support and framework to drive the growth of ski resort offer in the mid-60s to mid-70s. Resorts were then built according to a model known as "third generation resorts" which corresponds to a high altitude resort designed on the basis of a functional approach of space [...] to integrate the needs of every tourist from accomodation to leisure. This kind of resort has mainly been built in the "Tarentaise valley" (see Fig. 1). This clearly appears on the 2006–2007 season map with

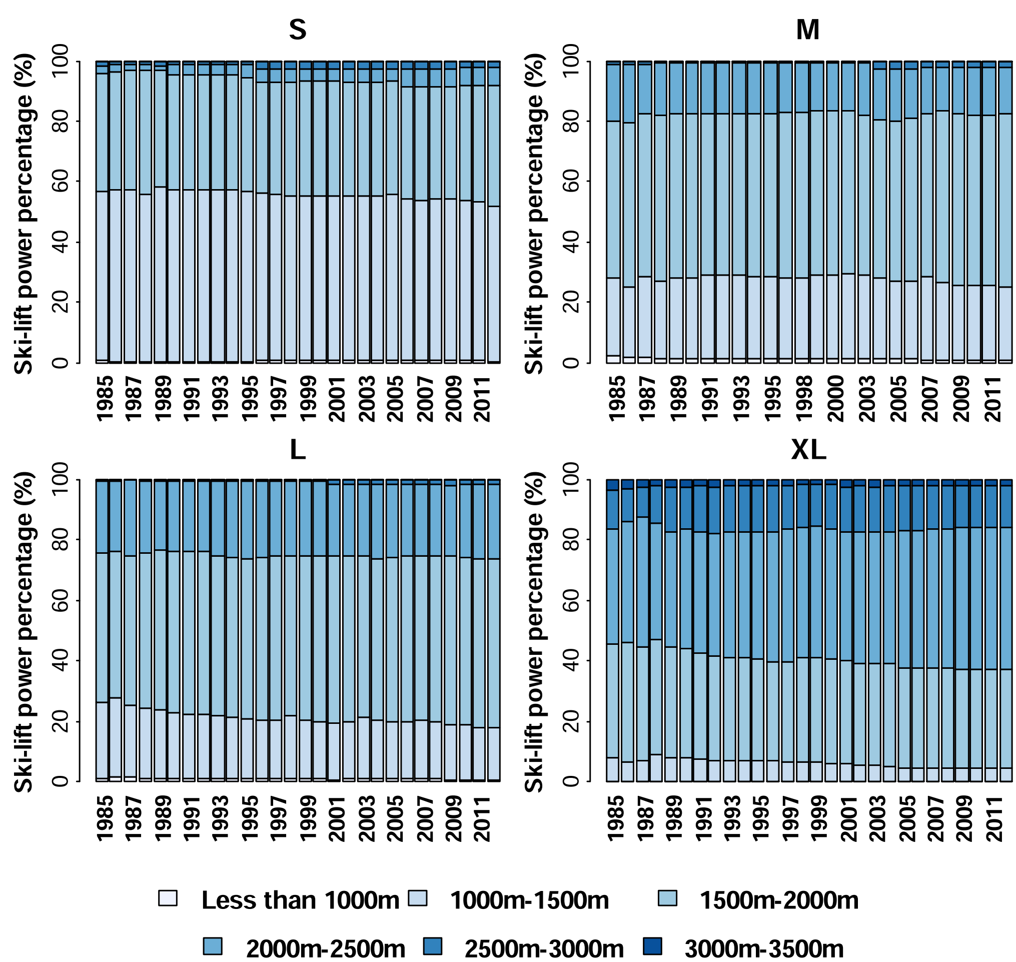

Fig. 11. Time evolution from 1985 to 2012 of the percentage of ski-lift power within given altitude ranges (less than 1000 m, 1000–1500 m, 1500–2000 m, 2000–2500 m, 2500–3000 m and above 3000 m) for the four ski resort classes (S, M, L and XL).

large ski-lift power and a rather good viability index thanks to their high altitude (see Fig. 7). Ski resorts in the Southern Alps correspond to 17.2% of the total ski-lift power, and play a smaller role in the French ski tourism industry than the Northern Alps. The higher variability of meteorological conditions in the Southern Alps may partly explain why ski resorts are preferentially located in the Northern Alps, but historical considerations related to the policy for the development of how high altitude ski resort must also be taken into account (George-Marcelpoil and François, 2012). Fig. 8 illustrates this contrast in terms of the altitudinal distribution of ski-lift power in the Southern and Northern French Alps.

Fig. 7 clearly shows the large difference between the snow seasons 2006–2007 and 2008–2009 but the link between snow conditions and skier day values is not straightforward. Even with a high viability index some resorts have relatively low level of skier days. This is analyzed below using correlations between the viability index, skier day values and ski-lift power (see Fig. 9). Fig. 9 demonstrates that skier day values and ski-lift power are extremely well correlated both during the snow seasons 2006–2007 and 2008–2009 with the same level of correlation (0.94 and 0.96, respectively). Regardless of the natural snow conditions, it appears that the size of ski resorts drives its level of activity (within a given snow season) better than the snow or meteorological conditions. Although this is not reflected in the correlation coefficient, inspection of Fig. 9 shows a larger scatter of the skier day/ski-lift power relationship for the snow season 2006–2007, displaying outliers to the good correlation between these two variables. The ski-lift power and viability index show a negligible correlation during the snow season 2008–2009 because virtually all resorts show high viability. In contrast, during the snow season 2006–2007 ski-lift power and viability are better correlated indicating that larger resorts are on average more viable than smaller ones. These results appear fully in line with the empirical assessment of the relationships between snow and meteorological conditions and skier days for the two seasons studied. The relationship with ski resort altitude is less marked. In the 2006–2007 season, correlation coefficients between average altitude of ski-lift (weighted by their power) and viability index or ski-lift power, respectively 0.74 and 0.48, are not very high which indicates that (1) the mean altitude does not explain itself the viability index although it plays a strong role and (2) ski-lift power is not directly linked to ski-lift altitude. There exist small resorts at high altitude, and vice versa, as shown in Fig. 10. In addition, since lower ski-lift power is key to feed upper ones in an operational resort because of the need to bring enough skiers to operate high altitude ski-lifts, it is not surprising that the link between mean ski-lift power and altitude is not strong. What appears more critical (and not dealt with here specifically) is how low (thus, how snowy) the bottom of the resort is. Nevertheless, the positive correlation between altitude and overall viability has for long encouraged resorts to invest in higher altitude facilities.

3.3. Long term evolution of ski-lift facilities

Different resorts do not renew their ski-lift facilities in the same way. They have to deal with their heritage and their dynamics are led by a self-sustaining mechanism. Given that a physical link must be maintained between the bottom and top of a ski area, bigger resorts were mostly built far away from existing towns in areas allowing access to higher areas for skiing. Over the period from 1985 to 2012, the fraction of ski-lift power at lower altitudes steadily decreased, as shown in Fig. 11. For all resorts, slices under 1500 m show a clear decreasing trend. This is even more marked for the XL resort type which tends to spread their ski areas to higher altitude. However, higher altitude investments remain limited since they are not available for every resort and since they do not necessarily offer the best conditions for skiing (very low temperatures and wind exposure). L resorts have preferred to equip between 1500 and 2000 m and XL resorts have chosen mainly the upper slice between 2000 and 2500 m while maintaining the lower one.

4. Conclusions and perspectives

The current study has demonstrated the technical feasibility and the interest of integrating physically-based numerical simulations of snow conditions spanning the entire French Alps using the SAFRAN–Crocus modeling suite into the geospatial database of ski resort BD Stations. Results from SAFRAN–Crocus for the period from 2000 to 2012 were integrated in the BD Stations allowing us to quantitatively compare steady (ski-lifts power) and seasonally variable (skier days) socio-economic data with the viability of the resort expressed as the weighted fraction of the ski resort surface area meeting the 100 day rule.

Two contrasted seasons were investigated with deeper attention: 2006–2007 and 2008–2009, the former having a strong deficit of snow on the ground (natural and machine made) and the latter having higher than usual snow amounts and skier day values. We found that the skier day values, representative of total skier flows in the resorts hence representative of their success, are strongly correlated to ski-lift power, i.e. the maximum capacity of the resort. The resort level of viability was found to be weakly correlated to skier-day and ski-lift power for the season 2008–2009 exhibiting good snow conditions through the entire French Alps, while the correlation was better for the snow season 2006–2007 where snow conditions were unfavorable. A multi-annual perspective beyond the two extreme cases reported here reveals that snow management practices, unaccounted for in the present study, most probably make a difference in terms of skier days and overall resort attractiveness and sustainability. This is particularly well illustrated by the fact that the 2006–2007 season was both unfavorable in terms of natural snow conditions and skier days, while the 2010–2011 season was unfavorable in terms of natural snow conditions but did not show the same drop of skier days than 2006–2007, most probably because meteorological conditions and/or snowmaking strategies were more appropriate for good snow conditions on ski slopes.

This work lays the foundation for a long-term tool addressing quantitatively the interactions between physical and socio-economic drivers of the mountain touristic sector (Strasser et al., 2014). Nevertheless, several aspects of this work deserve to be significantly improved, in order to be able to address the questions left unanswered in this first assessment. First of all, the work presented here only relies on numerical simulations of natural snow conditions, which are not representative of snow conditions on ski slopes. Ongoing developments in the Crocus model will allow us in the future to integrate this component in a manner which integrates the peculiar physical characteristics of machine made snow (Fierz et al., 2009) and the physical, snow management and regulatory bounds governing its production. The same applies to snow grooming, which should also be taken into account for a more accurate representation of the behavior of snow on ski slopes. Note that the integration of snow management practices in the modeling framework we developed will require us to allow feedback loops between snow conditions and socio-economic results, thereby leading to a much more complex system. Assessments including snow management practices should benefit from actual information in this area, but the lack of a solid framework to report such information in a manner that makes it possible to integrate in BD Stations — as basic as the number, type and location of snowmaking units for example — may hamper this aspect of the work in the near future.

Besides the natural/managed snow issue, the way the integrated viability index has been computed in our analysis is questionable mainly for two reasons. First of all, the 100 day rule can be criticized and improved, by focusing on snow mass rather than on snow depth and placing more weight on critical periods of the year (e.g. Christmas and winter holidays, see Damm et al., 2014). Second, the spatial structure of the ski resorts needs to be better represented. Our current system

Table 1
List of ski resorts used in this study, along with their SAFRAN massif, size class, total ski-lift power and altitude range.

Resort name	Resort size	Mountain range	Min altitude (m)	Max altitude (m)	Surface lifts (T-bars, rope tows)	Aerial lifts (chairlifts, gondolas)	Others (cable cars, funicular)	All ski-lifts	Power (persons ∗ km/h)
Clusaz (La)	L	Aravis	1028	2375	18	16	1	35	13,898
Grand Bornand (Le)	L	Aravis	940	2031	21	15	0	36	11,381
Hery sur Ugine	S	Aravis	912	1225	2	0	0	2	285
Manigod Croix Fry	S	Aravis	1416	1795	17	3	0	20	1875
Mont Saxonnex	S	Aravis	1050	1574	7	1	0	8	828
Montmin	S	Aravis	1110	1195	2	0	0	2	92
Nancy sur Cluses	S	Aravis	920	1558	4	0	0	4	354
Portes du Mont Blanc (Les) Combloux - Jaillet (Le) - Giettaz (La)	L	Aravis	988	2013	21	9	0	30	7854
Portes du Mont Blanc (Les) –Sallanche–Cordon	S	Aravis	1030	1538	7	0	0	7	1005
Reposoir (Le)	S	Aravis	950	1626	6	0	0	6	271
Saint Jean de Sixt	S	Aravis	951	1020	2	0	0	2	42
Saint Sixt — Orange Montisel	S	Aravis	1100	1166	3	0	0	3	88
Thorens Glieres	S	Aravis	1037	1153	1	0	0	1	76
Aillon le Jeune-Margeriaz	M	Bauges	945	1834	17	3	0	20	3600
Savoie Grand Revard	S	Bauges	1165	1549	15	2	0	17	1331
Semnoz (Le)	S	Bauges	1025	1696	11	2	0	13	1463
Seythenex–Sambuy (La)	S	Bauges	1140	1835	3	1	0	4	1161
Areches Beaufort	M	Beaufortain	1000	2137	11	4	0	15	4247
Crest Voland	M	Beaufortain	1200	1608	15	4	0	19	3611
Granier sur Aime	S	Beaufortain	1390	1661	2	0	0	2	222
Saisies (Les)	L	Beaufortain	432	2041	20	15	1	36	8029
Saisies (Les)	L	Beaufortain	432	2041	20	15	1	36	8029
Val d'Arly	L	Beaufortain	960	2053	36	9	0	45	8160
Chamrousse	L	Belledonne	1420	2253	19	8	0	27	6234
Collet d'Allevard (Le)	M	Belledonne	1421	2089	11	4	0	15	2627
Sept Laux (Les)	L	Belledonne	1300	2380	21	9	0	30	9782
Abondance	S	Chablais	950	1758	7	2	0	9	1402
Avoriaz–Morzine	XL	Chablais	970	2501	17	20	1	38	17,965
Bellevaux Hirmentaz	S	Chablais	1100	1612	15	3	0	18	2076
Bernex	S	Chablais	960	1871	11	3	0	14	2355
Brasses (Les)	S	Chablais	880	1495	11	3	0	14	2499
Carroz d'Araches (Les)	L	Chablais	1011	2125	11	7	0	18	6374
Chapelle d'Abondance (La)	M	Chablais	983	1797	7	5	0	12	3009
Chatel	L	Chablais	1100	2093	28	14	0	42	14,275
Col du Corbier	S	Chablais	1000	1615	6	2	0	8	637
Espace Roc d'Enfer	M	Chablais	945	1790	12	4	0	16	2838
Flaine	L	Chablais	1580	2482	11	12	3	26	12,974
Gets (Les)	L	Chablais	1000	2131	16	15	0	31	10,523
Habere Poche	S	Chablais	920	1505	4	3	0	7	1363
Lullin Col de Feu	S	Chablais	1085	1175	1	0	0	1	81
Morillon–Samoens–Sixt	L	Chablais	697	2118	19	16	1	36	12,691
Morzine Pleney Nyon	L	Chablais	980	2127	12	14	2	28	8467
Plaine-Joux	S	Chablais	1325	1718	8	0	0	8	747
Praz-de-Lys — Sommand	L	Chablais	1240	1961	19	6	0	25	5095
Thollon les Memises	S	Chablais	1026	1938	13	4	0	17	2331
Ancelle	S	Champsaur	1322	1811	12	2	0	14	1876
Orcieres Merlette	L	Champsaur	1363	2725	23	10	0	33	7959
Stations Village du Champsaur	M	Champsaur	1250	2240	25	4	0	29	3593
Col de Marcieu	S	Chartreuse	993	1350	5	0	0	5	220
Col de Porte	S	Chartreuse	1200	1701	5	1	0	6	590
Col du Granier — Desert d'Entremont (Le)	S	Chartreuse	990	1428	8	0	0	8	506
Saint Hilaire du Touvet	S	Chartreuse	260	1415	6	0	0	7	515
Saint Pierre de Chartreuse - Planolet (Le)	M	Chartreuse	900	1751	18	3	0	21	3261
Sappey en Chartreuse (Le)	S	Chartreuse	950	1344	5	0	0	5	365
Lus la Jarjatte	S	Devoluy	1160	1521	5	0	0	5	380
Massif du Devoluy	L	Devoluy	1455	2490	22	5	0	27	6767
Orres (Les)	L	Embrunais – Parpaillon	1418	2704	17	9	0	26	6532
Reallon	S	Embrunais–Parpaillon	1555	2114	5	2	0	7	1407
Risoul	L	Embrunais–Parpaillon	920	2551	17	9	0	26	6730
Alpe d'Huez (L')	XL	Grandes Rousses	1450	3318	41	26	2	69	19,828
Chazelet–Villar d'Arene	S	Grandes Rousses	1622	2164	8	1	0	9	1033
Oz–Vaujany	L	Grandes Rousses	1080	2817	15	7	2	24	7847
Bessans	S	Haute-Maurienne	1706	2079	3	0	0	3	184
Bonneval sur Arc	S	Haute-Maurienne	1800	2937	9	3	0	12	2023
Bramans	S	Haute-	1250	1304	1	0	0	1	16

(continued on next page)

Table 1 *(continued)*

Resort name	Resort size	Mountain range	Min altitude (m)	Max altitude (m)	Surface lifts (T-bars, rope tows)	Aerial lifts (chairlifts, gondolas)	Others (cable cars, funicular)	All ski-lifts	Power (persons ∗ km/h)
		Maurienne							
Norma (La)	M	Haute-Maurienne	1300	2742	9	7	0	16	4049
Val Cenis	L	Haute-Maurienne	1300	2737	18	15	0	33	12,464
Val Frejus	M	Haute-Maurienne	1550	2731	7	5	0	12	3241
Arcs (Les)–Peisey–Vallandry	XL	Haute-Tarentaise	810	3220	45	33	5	83	31,401
Rosière (La)	L	Haute-Tarentaise	1150	2572	19	7	0	26	6674
Sainte Foy Tarentaise	S	Haute-Tarentaise	1524	2612	3	4	0	7	2293
Tignes	XL	Haute-Tarentaise	1550	3459	28	24	2	54	25,328
Val d'Isere	XL	Haute-Tarentaise	1786	3197	21	24	5	50	23,976
Roubion les Buisses	S	Haut-Var–Haut-Verdon	1420	1898	7	1	0	8	720
Val d'Allos	L	Haut-Var–Haut-Verdon	1411	2500	25	14	2	41	9051
Val Pelens	S	Haut-Var–Haut-Verdon	1600	1737	3	0	0	3	168
Valberg–Beuil	M	Haut-Var–Haut-Verdon	437	2020	22	7	0	29	4898
Albiez Montrond	M	Maurienne	1480	2060	10	5	0	15	2695
Corbier (Le)–Saint Jean d'Arves–Saint Colomban des Villards	L	Maurienne	1083	2377	31	10	0	41	7948
Karellis (Les)	L	Maurienne	1550	2490	11	6	0	17	5116
Saint Sorlin d'Arves	L	Maurienne	1496	2590	9	8	0	17	7745
Toussuire (La)–Saint-Pancrace (Les Bottieres)	L	Maurienne	1284	2367	18	9	0	27	5972
Valloire	L	Maurienne	1408	2530	10	10	0	20	9626
Valmeinier	L	Maurienne	1383	2579	22	11	0	33	9683
Stations du Mercantour	XL	Mercantour	1151	2585	30	19	2	51	16,670
Chamonix	XL	Mont-Blanc	1000	3787	26	23	11	60	27,293
Contamines (Les)–Hauteluce	L	Mont-Blanc	1160	2437	17	12	0	29	9800
Houches (Les) - Saint-Gervais	L	Mont-Blanc	979	1892	12	8	1	21	5859
Megeve	L	Mont-Blanc	1059	2014	22	13	2	37	12,521
Saint Gervais Bettex	L	Mont-Blanc	568	2386	13	8	1	22	7014
Saint Nicolas de Veroce	M	Mont-Blanc	1173	2364	4	5	0	9	3713
Vallorcine La Poya	S	Mont-Blanc	1350	1502	4	0	0	4	163
Alpe du Grand Serre (L')	M	Oisans	1280	2221	12	3	0	15	3225
Col d'Ornon	S	Oisans	1330	1855	4	0	0	4	401
Deux Alpes (Les)	XL	Oisans	979	3642	35	28	3	66	24,045
Grave (La)	S	Oisans	1470	3532	1	0	0	3	915
Motte d'Aveillans (La)	S	Oisans	1290	1430	1	0	0	1	84
Notre Dame de Vaulx	S	Oisans	1030	1085	1	0	0	1	18
Saint Firmin Valgaudemar	S	Oisans	1350	1580	2	0	0	2	90
Villard Reymond	S	Oisans	1670	1712	1	0	0	1	37
Pelvoux–Vallouise	S	Pelvoux	1230	2237	8	1	0	9	1543
Puy St Vincent	L	Pelvoux	1410	2668	10	7	0	17	5569
Serre Chevalier	XL	Pelvoux	1200	2750	51	26	2	79	25,988
Station du Queyras	L	Queyras	1450	2801	38	5	0	43	6240
Montgenevre	L	Thabor	1753	2581	16	13	0	29	8616
Nevache	S	Thabor	1585	1707	3	0	0	3	112
Col Saint Jean	M	Ubaye	1134	2450	10	4	0	14	2935
Pra-Loup	L	Ubaye	1578	2500	15	9	1	25	7216
Stations de l'Ubaye	L	Ubaye	1370	2427	32	6	0	38	5815
Vars	L	Ubaye	1610	2721	26	10	0	36	9068
Aussois	M	Vanoise	1300	2670	8	6	0	14	3089
Courchevel	XL	Vanoise	1260	2919	52	41	4	97	38,267
Menuires (Les)	XL	Vanoise	1389	2841	18	21	1	40	20,823
Meribel les Allues	XL	Vanoise	612	2701	15	16	0	31	15,227
Notre Dame du Pre	S	Vanoise	1255	1510	3	0	0	3	225
Orelle	L	Vanoise	890	3242	1	4	0	5	5130
Plagne (La)	XL	Vanoise	1200	3167	76	42	3	121	36,038
Pralognan	M	Vanoise	1400	2340	13	4	1	18	3680
Saint Francois Longchamp	L	Vanoise	1394	2514	16	6	0	22	5688
Val Thorens	XL	Vanoise	1718	3186	12	16	3	31	18,780
Valmorel	L	Vanoise	1210	2401	19	9	1	29	8629
Autrans	S	Vercors	1032	1650	15	1	0	16	1709
Col de l'Arzelier	S	Vercors	1000	1477	3	1	0	4	470
Col du Rousset	S	Vercors	1251	1695	10	1	0	11	1289

Table 1 *(continued)*

Resort name	Resort size	Mountain range	Min altitude (m)	Max altitude (m)	Surface lifts (T-bars, rope tows)	Aerial lifts (chairlifts, gondolas)	Others (cable cars, funicular)	All ski-lifts	Power (persons * km/h)
Font d'Urle — Chaud Clapier	S	Vercors	1279	1650	12	0	0	12	600
Gresse en Vercors	S	Vercors	1000	1703	10	1	0	11	1252
Lans en Vercors	S	Vercors	1013	1801	15	0	0	15	1879
Meaudre	S	Vercors	971	1577	9	2	0	11	1645
Rencurel	S	Vercors	1050	1233	3	0	0	3	221
Saint Nizier	S	Vercors	1161	1200	2	0	0	2	50
Villard de Lans–Correncon	L	Vercors	1095	2052	24	10	0	34	8204
Total			260	3787	1870	922	64	2859	812,448

integrates a pixel based binary viability index according to its fractional contribution to total ski-lift power. This already attempts to put more weight on the portions of the resort that most contribute to its operation. However differential emphasis could also be placed on lower/higher altitude areas (e.g. Steiger, 2010), including the possibility or not to reach the resort bottom by ski or cable car in case of insufficient snow amounts. Instead of using ski-lift envelopes to represent ski areas, actual ski slopes' geographical information shall be used, but this information is generally not available in a condensed, thus usable, form.

Pending that some of the limits identified above are addressed, we believe that the tool that has emerged from the information crossing between BD Stations and SAFRAN–Crocus has a strong potential for integrated assessments of socio-economic and physical understanding of the functioning of ski resorts which are a significant component of both mountain economy and French tourism industry. Because it integrates at its heart the geographic information about ski resorts, applications of this tool with downscaled climate projections will allow us to provide more relevant assessments of the possible future state of this economic sector than climate projections for a fixed altitude range, which are not necessarily appropriate for projections in the complex world of mountain ski resorts. Here again, accounting for snow management practices in a physically- and socioeconomically-sound manner will be key to providing relevant and realistic assessments of the impact of climate change on ski tourism.

Acknowledgments

The BD Stations project benefited from funding by Comité de Massif des Alpes and FEDER (No. PRESAGE 39.992). We thank Région Rhône Alpes (ARC Environnement) and LabEx OSUG@2020 (ANR10 LABX56) for funding through the GANESH project. Irstea and CNRM-GAME are part of LabEx OSUG@2020 (ANR10 LABX56). Irstea is a member of the LabEx ITEM (ANR10 LABX50-01). STRMTG and DSF are acknowledged for providing the FIRM and socio-economic data, respectively. Spatial information freely made available by IGN greatly facilitated this work. We further thank C. Coléou and P. Spandre for stimulating discussions, Y. Durand, G. Giraud and L. Mérindol for providing SAFRAN data used in this study and F. Bray, E. Maldonado and J.-B. Barré for technical help related to the BD Stations. We thank two anonymous reviewers for their encouragements and comments which helped in improving the manuscript.

References

Abegg, B., 1996. Klimaänderung une Tourismus — Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen. Schlussbericht NFP 31. Zürich.

Abegg, B., Agrawala, S., Crick, F., de Montfalcon, A., 2007. Climate change impacts and adaptation on winter tourism. In: Agrawal, S. (Ed.), Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management. OECD Publishing, Paris, pp. 25–60.

Achin, C., George-Marcelpoil, E., 2013. Sorties de pistes pour la performance des stations de sports d'hiver. Tour. Territ./Tour. Territ. 3, 67–92.

Beniston, M., 1997. Variations of snow depth and duration in the Swiss Alps over the last 50 years: links to changes in large-scale climatic forcings. Clim. Chang. 3, 281–300.

Brun, E., David, P., Sudul, M., Brunot, G., 1992. A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting. J. Glaciol. 38 (128), 13–22.

Damm, A., Köberl, J., Prettenthaler, F., 2014. Does artificial snow production pay under future climate conditions? — a case study for a vulnerable ski area in Austria. Tour. Manag. 43, 8–21. http://dx.doi.org/10.1016/j.tourman.2014.01.009, 2014.

Durand, Y., Brun, E., Mérindol, L., Guyomarch, G., Lesaffre, B., Martin, E., 1993. A meteorological estimation of relevant parameters for snow models. Ann. Glaciol. 18, 65–71.

Durand, Y., Giraud, G., Brun, E., Mérindol, L., Martin, E., 1999. A computer-based system simulating snowpack structures as a tool for regional avalanche forecasting. J. Glaciol. 45, 469–484.

Durand, Y., Laternser, M., Giraud, G., Etchevers, P., Lesaffre, L., Mérindol, L., 2009a. Reanalysis of 44 yr of climate in the French Alps (1958–2002): methodology, model validation, climatology, and trends for air temperature and precipitation. J. Appl. Meteorol. Climatol. 48, 29–449.

Durand, Y., Laternser, M., Giraud, G., Etchevers, P., Mérindol, L., Lesaffre, B., 2009b. Reanalysis of 47 yr of climate in the French Alps (1958–2005): climatology and trends for snow cover. J. Appl. Meteorol. Climatol. 48, 2487–2512.

Elsasser, H., Bürki, R., 2002. Climate change as a threat to tourism in the Alps. Clim. Res. 20, 253–257.

Essery, R., Morin, S., Lejeune, Y., Ménard, C.B., 2013. A comparison of 1701 snow models using observations from an alpine site. Adv. Water Resour. 55, 131–148. http://dx.doi.org/10.1016/j.advwatres.2012.07.013.

Fauve, M., Rhyner, H., Lüthi, A., Schneebeli, M., Lehning, M., 2008. Putting snow knowledge into the development of winter sports equipment. Sports Technol. 1 (2–3), 145–151.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K., Sokratov, S.A., 2009. The international classification for seasonal snow on the ground. IHP-VII Technical Documents in Hydrology n 83, IACS Contribution n 1.

Flagestad, A., Hope, C.A., 2001. Strategic success in winter sports destinations: a sustainable value creation perspective. Tour. Manag. 22, 445–461. http://dx.doi.org/10.1016/S0261-5177(01)00010-3.

François, H., 2007. De la station ressource pour le territoire au territoire ressource pour la station. Le cas des stations de moyenne montagne périurbaines de Grenoble(PhD thesis) Université Joseph Fourier, Grenoble (352 pp.).

François, H., George-Marcelpoil, E., Fablet, G., Bray, F., Achin, C., Torre, A., Barré, J.-B., 2012. Atlas des stations du massif des Alpes, Irstea, (103 pp.).

George-Marcelpoil, E., François, H., 2012. From creating to managing resorts. Rev. Géogr. Alp.-| J. Alp. Res. 100 (3). http://dx.doi.org/10.4000/rga.1925.

Gerbaux, F., 2004. Landmarks: European agricultural and regional policies in favour of less-favoured areas and mountain areas. Rev. Géogr. Alp. 92 (2), 14–16. http://dx.doi.org/10.3406/rga.2004.2288.

Gerbaux, F., Marcelpoil, E., 2006. Governance of mountain resorts in France: the nature of the public–private partnership. Rev. Géogr. Alp. 94 (1), 20–31. http://dx.doi.org/10.3406/rga.2006.2381.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps—a review. Sci. Total Environ. http://dx.doi.org/10.1016/j.scitotenv.2013.07.050.

Guily, L., 1991. L'exploitation technique des pistes de ski alpin dans le domaine skiable francais, (Thèse de doctorat).

Koenig, U., Abegg, B., 1997. Impacts of climate change on winter tourism in the Swiss Alps. J. Sustain. Tour. 5 (1), 46–58.

Lafaysse, M., Morin, S., Coléou, C., Vernay, M., Serça, D., Besson, F., Willemet, J.-M., Giraud, G., Durand, Y., 2013. Towards a new chain of models for avalanche hazard forecasting in French mountain ranges, including low altitude mountains. Proceedings of the International Snow Science Workshop Grenoble — Chamonix Mont-Blanc — 2013, 7–11 October, Grenoble, France, pp. 162–166.

Lafaysse, M., Hingray, B., Mezghani, A., Gailhard, J., Terray, L., 2014. Internal variability and model uncertainty components in future hydrometeorological projections: the Alpine Durance basin. Water Resour. Res. 50, 3317–3341. http://dx.doi.org/10.1002/2013WR014897.

Lorit, J.-F., 1991. Enquête sur les difficultés des stations de sports d'hiver. Ministère de l'intérieur, Paris.

Luterbacher, J., Liniger, M.A., Menzel, A., Estrella, N., Della-Marta, P.M., Pfister, C., Rutishauser, T., Xoplaki, E., 2007. Exceptional European warmth of autumn 2006 and winter 2007: historical context, the underlying dynamics, and its phenological impacts. Geophys. Res. Lett. 34, L12704. http://dx.doi.org/10.1029/2007GL029951.

Luthe, T., Roth, R., Elsasser, H., 2008. SkiSustain — sustainable management of ski destinations in the contexte of tourism demand, ski area stratégies and global change. Managing Alpine Future. Strategies in Global Change. Innsbruck, 15–17 Octobre 2007. Innsbruck University Press.

Luthe, T., Wyss, R., Schuckert, M., 2012. Network governance and regional resilience to climate change: empirical evidence from mountain tourism communities. Reg. Environ. Chang. http://dx.doi.org/10.1007/s10113-012-0294-5.

Martin, E., Brun, E., Durand, Y., 1994. Sensitivity of the French Alps snow cover to the variation of climatic variables. Ann. Geophys. 12, 469–477.

Pascal, R., 1993. Problèmes structurels des stations de moyenne montagne. Ministre de l'équipement, des Transports et du Tourisme, Paris.

Rousselot, M., Durand, Y., Giraud, G., Mérindol, L., Dombrowski-Etchevers, I., Déqué, M., Castebrunet, H., 2012. Statistical adaptation of ALADIN RCM outputs over the French Alps — application to future climate and snow cover. Cryosphere 6, 785–805. http://dx.doi.org/10.5194/tc-6-785-2012.

Scott, D., McBoyle, G., 2007. Climate change in the ski industry. Mitig. Adapt. Strateg. Glob. Chang. 12, 1411–1431.

Scott, D., McBoyle, G., Mills, B., 2003. Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. Clim. Res. 23 (2), 171.

Steger, C., Kotlarski, S., Jonas, T., Schär, C., 2013. Alpine snow cover in a changing climate: a regional climate model perspective. Clim. Dyn. 41, 735–754.

Steiger, R., 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. Clim. Res. 43 (3), 251–262.

Steiger, R., Mayer, M., 2008. Snowmaking and climate change. Future options for snow production in Tyrolean ski resorts. Mt. Res. Dev. 28 (3/4), 292–298.

Strasser, U., Vilsmaier, U., Prettenhaler, F., Marke, T., Steiger, R., Damm, A., Hanzer, F., Wilcke, R.A.I., Stötter, J., 2014. Coupled component modelling for inter- and transdisciplinary climate change impact research: dimensions of integration and examples of interface design. Environ. Model Softw. 60, 180–187. http://dx.doi.org/10.1016/j.envsoft.2014.06.014.

Svensson, B., Nordin, S., Flagestad, A., 2005. A governance perspective on destination development — exploring partnerships, clusters and innovation systems. Tour. Rev. 60 (2).

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., Willemet, J.-M., 2012. The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. Geosci. Model Dev. 5, 773–791. http://dx.doi.org/10.5194/gmd-5-773-2012.