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Observation et modélisation des interactions entre conditions d'enneigement et activité des stations de sports d'hiver dans les Alpes françaises

Pierre Spandre

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THÈSE

Pour obtenir le grade de

DOCTEUR de la communauté

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préparée au sein de

IRSTEA - Développement des Territoires Montagnards
Météo-France/CNRS, CNRM, Centre d'Etudes de la Neige
et de l'école doctorale **Terre, Univers, Environnement**

Observation et modélisation des interactions entre conditions d'enneigement et activité des stations de sports d'hiver dans les Alpes françaises

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Résumé [Français]

Les interactions dynamiques des conditions d'enneigement avec l'activité touristique des stations de sport d'hiver reposent sur de multiples enjeux sociaux, économiques, environnementaux et climatiques intégrés par les élus chargés du développement des territoires de montagne et industriels responsables de l'exploitation des domaines skiables. Depuis l'expérience vécue de la vulnérabilité des domaines skiables au déficit d'enneigement au début des années 1990 et plus encore depuis l'introduction des problématiques du changement climatique dans le débat public au début des années 2000, l'attente de la part des décideurs politiques et des professionnels de la neige pour des éléments fiables et pertinents sur l'impact du climat sur l'activité des sports d'hiver - dans laquelle s'intègre ce travail - n'a cessé de croître. Ce travail s'est attaché à la compréhension du rôle intégrateur de l'opérateur de domaine skiable dans son approche socio-économique d'une part et nivo-climatologique d'autre part de la gestion de la neige dans sa station dans le but de développer une chaîne de modélisation de la dynamique des interactions entre les conditions d'enneigement (variabilité, imprévisibilité) et les activités humaines (objectifs, moyens). Un état des lieux a été établi sur les priorités poursuivies, les moyens mis en œuvre (damage, neige de culture) et les contraintes subies (météorologiques, organisationnelles, structurelles) par les gestionnaires de domaines skiables dans leurs opérations quotidiennes de gestion de la neige grâce à une enquête auprès de 55 stations françaises et aux échanges réguliers avec quatre stations partenaires de ce travail (Autrans, Tignes, Chamrousse et Les Deux Alpes). Une modélisation physique des impacts de la gestion de la neige a été développée sur la base d'un modèle de neige et confrontée à des observations réalisées au cours de deux saisons hivernales consécutives dans ces quatre stations partenaires. Ces éléments ont été intégrés dans une chaîne de modélisation couplée permettant des études spatialisées des conditions d'enneigement et in fine la détermination d'indicateurs de la viabilité de l'enneigement à l'échelle de la station, dans l'ensemble des Alpes françaises. Cette méthode extrapolable à l'ensemble des massifs français a été appliquée dans les Alpes françaises sur la période passée 1958 – 2014 et a révélé la corrélation des indicateurs d'enneigement avec les données économiques des stations de sport d'hiver. Notre approche a ainsi montré sa pertinence pour des études prospectives de l'impact du changement climatique et/ou des infrastructures des domaines skiables sur la viabilité de l'enneigement et ses conséquences pour l'activité économique des stations de sport d'hiver.

Mots clefs : Stations ; Alpes françaises ; Gestion de la neige ; Damage ; Neige de culture ; Simulation ; Rendement neige de culture ; Pratiques professionnelles

Abstract [English]

The industrial activity of ski resorts is based upon multiple concerns including social, economic, environmental and climatic issues which ski resorts stakeholders have to cope with. In the early 1990's ski resorts experienced several consecutive seasons with poor snow conditions in the European Alps when climate and environmental questions were discussed as a global concern after the United Nations held their first international conferences on climate change. This raised the interest of ski resorts stakeholders and representatives of host communities for reliable and relevant indicators of climate induced impacts on snow conditions and on the related economic activity of ski resorts. This research focused on the role played by ski resorts operators in crossing socio-economic concerns with meteorological and snow concerns, to provide a modelling approach of dynamics and interactions between snow conditions (variability, low predictability) and human activities (defined by purposes and means). The objectives pursued by operators, the means they employ (grooming, snowmaking) and constraints they face (meteorological, structural or organization issues) have been investigated through a survey of 55 French ski resorts and frequent discussions with four partner ski resorts (Tignes, Autrans, Les Deux Alpes, Chamrousse). A physically based modelling approach of the impact of grooming and snowmaking on snow properties was integrated in a snowpack model and evaluated with respect to field observations in the four partner ski resorts over two consecutive winter seasons. This was crossed with a socio economic database of ski resorts to provide an explicit spatial modelling of managed snow conditions on ski slopes for the entire French Alps ski resorts. This method was applied for the 1958 - 2014 period and snow indicators were defined and computed, revealing a significant correlation of snow reliability indicators with economic data on ski resorts. This approach therefore proved its ability to provide relevant indicators of snow conditions in ski resorts with respect to economic implications and may be used for further prospective investigations of evolutions of facilities and/or climate change impacts on snow conditions and the related economy of the ski industry.

Keywords : Ski resorts; French Alps; Snow management; Grooming; Snowmaking; Snowpack model; Snowmaking efficiency; Professional practices;

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Chapitre 1

Observation et modélisation des interactions entre les conditions d'enneigement et l'activité des stations de sports d'hiver dans les Alpes françaises

Résumé [Français]

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1.1 Le ski à la croisée des chemins

A la suite des élections régionales de 2015 et la fusion des régions Auvergne et Rhône-Alpes, un plan d'investissement dans les activités de sports d'hiver a été annoncé publiquement avec l'objectif de "sécuriser l'enneigement et l'emploi" par le financement d'enneigeurs, notamment dans "les petites stations [qui] permettent à nos jeunes d'apprendre sans que ce ne soit trop cher"¹. Cette annonce a été saluée par les acteurs de la filière² tandis que d'autres ont dénoncé l'abandon des territoires de montagnes hors domaines skiables³ par un plan "neuf d'il y a quarante ans en arrière"⁴. Pour les opposants à ce plan, la montagne ne peut se limiter à l'industrie de la neige devenue trop élitiste et qui ne correspondrait pas plus aux aspirations des habitants qu'à celle des visiteurs d'aujourd'hui, interrogeant la pertinence de telles mesures dans un contexte de changement climatique. Ce nouvel épisode d'un débat déjà riche souligne les multiples facettes de l'activité des stations de sport d'hiver dont le développement repose au bout du compte sur un arbitrage nécessairement politique, seul à même d'établir l'équilibre entre intérêts, inconvénients, opportunités et risques sociaux, environnementaux, économiques et climatiques soulevés par l'industrie du ski.

Une industrie majeure A la fin de la seconde guerre mondiale le modèle économique fordiste a été adopté dans la plupart des filières industrielles en Europe et en France auquel l'agriculture n'a pas échappé. La recherche du rendement a écarté les territoires de montagne au climat et à la topographie trop rudes d'une compétition perdue d'avance. L'opportunité des activités des sports d'hiver s'est présentée pour ces territoires lorsque que les congés payés et une demande pour un tourisme de masse sont apparus dans les années 1950 (Francois and George-Marcelpoil, 2012). Les stations de la première heure (Chamonix, Val d'Isère, Megève) connaissent alors un essor spectaculaire tandis que de nouveaux complexes (Les Arcs, La Plagne, Isola 2000, etc.) entièrement dédiés à la pratique des sports d'hiver sont créés dans des espaces vierges jusque là. La construction immobilière finance des remontées mécaniques qui assurent en retour l'attractivité des stations et garantissent le remplissage des carnets de réservation (Fablet, 2013). A cette époque, la qualité de l'enneigement ne fait aucun doute et la progression de la fréquentation est forte. Au milieu des années 1980, l'industrie du ski est définitivement un acteur majeur de l'économie des territoires de montagnes. En 2014, 20% de la richesse produite en Savoie et Haute-Savoie est directement liée aux sports d'hiver (Lecuret et al., 2014). La France compte aujourd'hui dix des trente plus grandes stations de sports d'hiver dans le monde situées dans les Alpes françaises, et se place parmi les destinations les plus recherchées par les skieurs du monde entier avec les Etats-Unis et l'Autriche ou encore l'Italie, la Suisse et le Canada (Abegg et al., 2007; Vanat, 2014). La fédération des Domaines Skiables de France (DSF) annonce ainsi que pour chaque euro dépensé dans les remontées mécaniques, sept euros sont dépensés dans l'économie locale (hébergement, restauration, loisirs, etc.), assurant 150 000 emplois dans les régions de montagne en France (DSF, 2014).

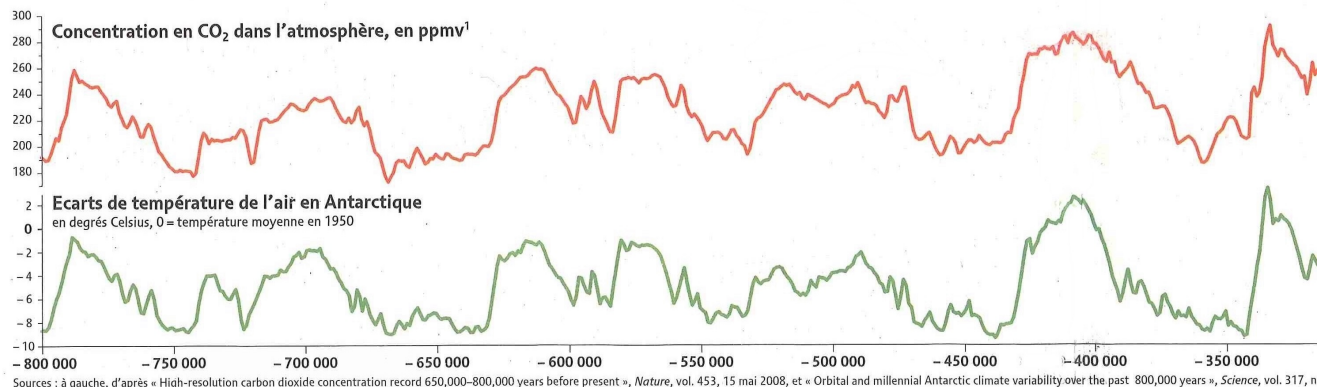
Fragilités structurelles Le courant des années 1980 souligne pour la première fois les fragilités structurelles d'une industrie portée par la construction immobilière et exposée aux aléas naturels de l'enneigement. La construction d'immobilier neuf est soutenue par le besoin de renouvellement du parc

1. Laurent Wauquiez, 3 mai 2016, France 3 Régions

2. "Plan Neige Montagne : un lancement aux sons des canons!", Le Dauphiné Libéré, 3 mai 2016

3. Lettre ouverte de Frédi Meignan, président de Mountain Wilderness à Laurent Wauquiez et Gilles Chabert, 12 mai 2016.

4. Claude Comet, ex conseillère régionale chargée du tourisme et de la montagne, 4 mai 2016, France 3 Régions.



de remontées mécaniques pour des installations plus modernes et attractives et par l'urbanisation touristique que les Jeux Olympiques d'Albertville (1992) ont largement consolidée (Fablet, 2013). Les remontées mécaniques des domaines skiables se trouvant alors sous dimensionnées par rapport à la capacité d'accueil des stations, de nouvelles installations ont été envisagées et construites, engageant de ce fait l'économie des stations de sport d'hiver dans un cycle de croissance perpétuelle de l'immobilier (Pascal, 1993) souligné par les difficultés actuelles de rénovation et de renouvellement de ce parc. L'occurrence de plusieurs hivers consécutifs de faible enneigement (1989,1990,1993) a révélé à la même période la vulnérabilité des sports d'hiver au manque de neige du fait de l'exclusivité du ski comme seule activité de loisir (Lorit, 1991). Le manque de neige généralisé au cours de ces hivers a incité les domaines skiables à s'équiper en enneigeurs dans le but d'atténuer les effets de la variabilité naturelle du climat et des conditions d'enneigement. Ces équipements n'ont cessé de croître depuis les années 1990, soutenus par une logique de la branche professionnelle pour la garantie "neige" et la satisfaction du client skieur. Cette logique s'est trouvée renforcée depuis les années 2000 et l'introduction dans le débat public de la problématique du changement climatique⁵, les équipements de neige de culture constituant le principal outil d'atténuation des effets du changement climatique pour les domaines skiables (Trawöger, 2014).

Observations du changement climatique La prise de conscience publique du changement climatique au cours des années 1990 repose sur de nombreux travaux révélant un réchauffement significatif des températures à l'échelle du globe accompagné de changements du système climatique sans précédents depuis des dizaines, voire des milliers d'années (IPCC, 2014). Les rapports du Groupement Intergouvernemental sur l'Evolution du Climat (GIEC) établissent également la responsabilité des activités humaines dans l'évolution récente du climat en lien avec l'augmentation remarquable des concentrations de gaz à effet de serre (GES) dans l'atmosphère⁶, notamment depuis 1950 (Figure 1.1).

5. La troisième conférence des parties (COP3) de la Convention Cadre des Nations Unies sur les changements climatiques s'est tenue à Kyoto (Japon) en 1997 et donné lieu au protocole de Kyoto (entrée en vigueur en 2005), le premier accord de référence internationale sur le climat.

6. Les gaz tels que la vapeur d'eau, le dioxyde de carbone ou le méthane présents dans l'atmosphère (GES) contribuent au processus physique naturel dit d'effet de serre. Ces GES absorbent une partie du rayonnement solaire et infrarouge terrestre et émettent un rayonnement infrarouge vers la Terre, deux actions combinées qui contribuent à un gain énergétique pour la surface de la Terre participant naturellement à son bilan énergétique (Trenberth et al., 2009). Cet équilibre thermique s'est trouvé perturbé par l'augmentation sans précédent depuis 800 000 ans des concentrations de GES dans notre atmosphère depuis 1950 dont les activités humaines constituent la source majeure, sans doute possible aujourd'hui (IPCC, 2014).

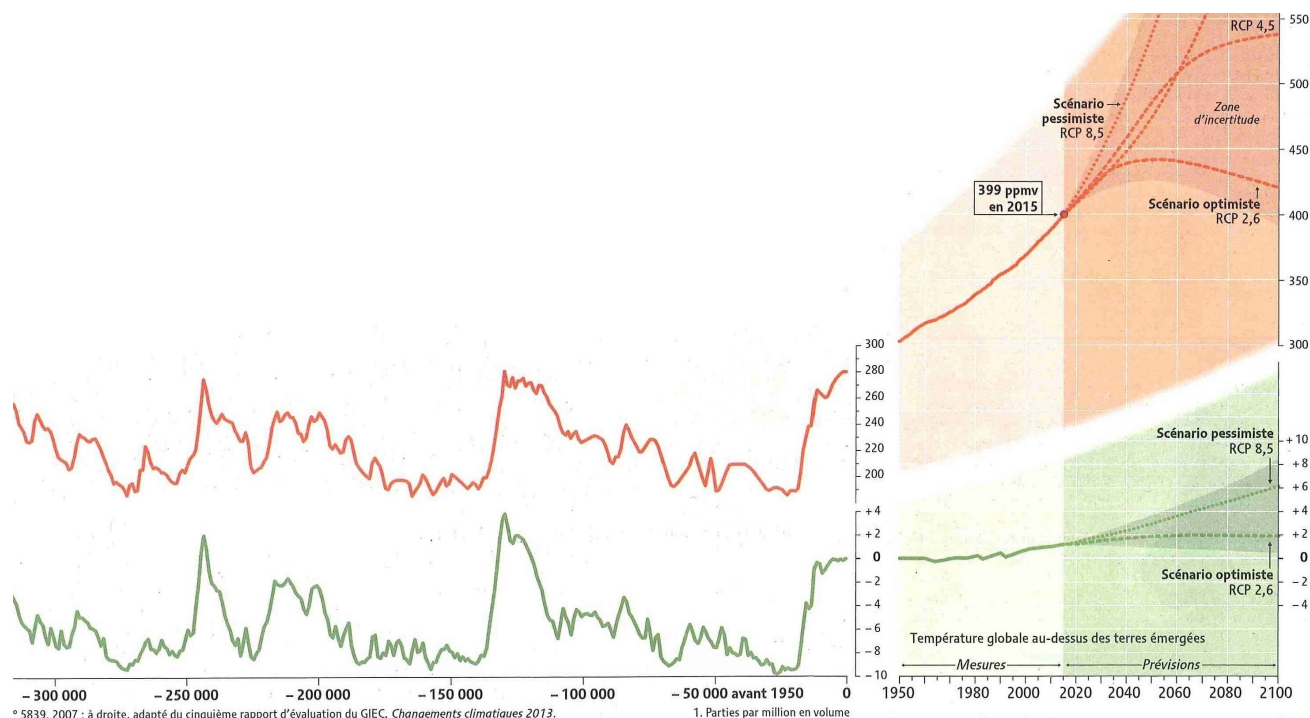


FIGURE 1.1 – Concentration en dioxyde de carbone (CO₂) dans l’atmosphère et température de l’air en Antarctique (écart à la température moyenne en 1950) depuis - 800 000 ans avant notre ère et projections pour le 21^{ème} siècle (Martin, 2015)

Entre 1880 et 2012 l’évolution observée de la température moyenne à l’échelle du globe est estimée à +0.85°C, avec une probabilité de 90% que cette évolution se situe entre +0.65 et +1.06°C (IPCC, 2014). Ces évolutions ne sont pas homogènes à la surface de la Terre avec des réchauffements plus marqués notamment dans les massifs montagneux. Gobiet et al. (2014) ont estimé que la température moyenne dans les Alpes avait augmenté deux fois plus vite que la température moyenne dans l’hémisphère Nord avec une évolution assez homogène de +2°C sur l’ensemble des Alpes depuis la fin du 19^{ème} siècle. Durand et al. (2009b) ont calculé une évolution de +1.15°C des températures moyennes de l’air entre 1958 et 2002 dans les Alpes françaises. Au cours de cette même période, les quantités totales de précipitations n’ont pas connu d’évolution statistiquement significative dans la plupart des cas étudiés, leur évolution restant soumise à une forte variabilité spatiale et interannuelle (Beniston, 2006; Gobiet et al., 2014). Les conditions d’enneigement ont par conséquent évolué sous l’influence de la température qui gouverne en particulier la limite pluie-neige lors des épisodes de précipitations. Une hausse de température impliquant une élévation de cette limite entraîne à altitude égale une durée d’enneigement plus courte et une accumulation de neige moins importante au cours de la saison (Durand et al., 2009a; Marty, 2013). A titre d’exemple, la durée de la saison avec de la neige au sol a diminué de 6 jours par décennie entre 1960 et 2011 sur le site expérimental du Col de Porte (Chartreuse, France), à 1325 m d’altitude tandis que la hauteur moyenne de neige entre le 1^{er} décembre et le 30 avril a diminué de 13 cm par décennie (Lesaffre et al., 2012). L’ensemble de la communauté scientifique s’accorde sur la tendance de cette évolution des températures et du manteau neigeux, même si l’amplitude des effets demeure variable entre les massifs et les différentes altitudes (Gilaberte-Búrdalo et al., 2014; Gobiet et al., 2014).

En 2014, un nouveau rapport du GIEC a proposé quatre trajectoires possibles d’évolution des concentrations de gaz à effet de serre au cours du 21^{ème} siècle, baptisées RCP⁷(IPCC, 2014).

7. Representative Concentration Pathway (RCP)

Ces trajectoires⁸ incluent deux scénarii correspondant à une poursuite de la croissance démographique et économique que nous connaissons actuellement, sans politique environnementale (RCP6.0 et 8.5), un scénario de prise en compte du changement climatique et de stabilisation des émissions de GES (RCP4.5) et un scénario de réduction drastique des émissions de GES (RCP2.6). Une augmentation de la température moyenne à l'échelle de la planète limitée à +2°C correspondrait selon le GIEC à un cumul d'émissions de GES par les activités humaines depuis le début de l'ère industrielle de l'ordre de 2900 GtCO₂⁹ tandis que ce cumul atteignait 1900 GtCO₂ en 2011 (IPCC, 2014). Le seul scénario RCP permettant d'atteindre cet objectif de limitation du réchauffement à un maximum de +2°C à la fin du 21^{ème} siècle est le RCP2.6, le plus optimiste. Du fait de l'inertie du système climatique, les évolutions pour la première moitié du siècle sont proches entre les scénarii avec une augmentation projetée des températures de +0.3 à +0.7°C en 2035 par rapport à la période 1986 - 2005. Les massifs montagneux continueront à subir des effets plus marqués que la moyenne mondiale avec une élévation projetée de la température moyenne de +1.5°C au cours de la période 2021 - 2050 par rapport à la période référence 1961 - 1990 (Rousselot et al., 2012; Gobiet et al., 2014). L'enneigement sera impacté par ces changements de température à toutes les altitudes et en particulier aux altitudes moyennes, en dessous de 1500 à 2000 m (Rousselot et al., 2012; Kotlarski et al., 2012; Marty, 2013). Abegg et al. (2007) ont estimé que la limite d'altitude correspondant à une durée de 100 jours avec au moins 30 cm de neige au sol s'élèverait de 150 m par degré Celsius d'augmentation de la température moyenne annuelle de l'air. Rousselot et al. (2012) estiment que l'enneigement moyen sur les mois de décembre, janvier et février va diminuer d'au moins 30% sur la période 2021 - 2050 par rapport à 1961 - 1990. L'expérience à plusieurs reprises depuis la fin des années 1980 de la vulnérabilité des domaines skiables aux conditions d'enneigement associée à la perspective d'une évolution significative de ces conditions a soulevé un fort intérêt de la part des décideurs politiques comme des professionnels pour des éléments de réponse par la communauté scientifique sur les impacts du changement climatique sur l'activité des stations de sports d'hiver.

Interactions climat - activités humaines L'enjeu pour la fourniture d'éléments les plus pertinents, objectifs et fiables possibles aux décideurs politiques et industriels réside dans le caractère dynamique et interactif de la relation entre les conditions climatiques (météorologie, enneigement) et les activités des stations de sport d'hiver (gestion de la neige, réussite économique). La prise en compte de ces interactions (Figure 1.2) entre activités humaines (attentes et interventions) et conditions d'enneigement (variabilité, imprévisibilité) constitue l'objectif général de ce travail et repose sur deux piliers. D'abord l'identification des priorités poursuivies, des moyens mis en oeuvre et des contraintes subies par les gestionnaires dans leurs opérations quotidiennes pour la production d'un cadre synthétique et modélisable des pratiques de gestion de la neige dans les domaines skiables Français (Chapitres 2 et 3). Ensuite le développement et la confrontation à des observations, toute action humaine connue, d'une chaîne de modélisation physique des conditions d'enneigement dans les domaines skiables (Chapitres 4 et 5). Une fois intégrés, ces deux piliers permettent de modéliser à une échelle spatiale fine les conditions d'enneigement dans l'ensemble des domaines skiables des Alpes françaises qui prennent en compte les méthodes de gestion de la neige telles que le damage et la production de neige de culture. Cette approche systématique permet la détermination d'indicateurs pertinents et objectifs sur les conditions d'enneigement pour des études prospectives de l'activité socio-économique des domaines skiables des

8. Le chiffre correspond à une évolution du rayonnement incident net à la fin du siècle. Par exemple, le RCP8.5 correspond à une augmentation de +8.5 W m⁻² du forçage radiatif à la surface de la Terre entre la période pré-industrielle et 2100

9. 1 GtCO₂ ou 1 million de tonnes d'équivalent carbone, CO₂ (IPCC, 2014)

Alpes françaises (Figure 1.2) dont le potentiel et la fiabilité sont discutés dans une analyse rétrospective de la période 1958 - 2014 (Chapitre 6).

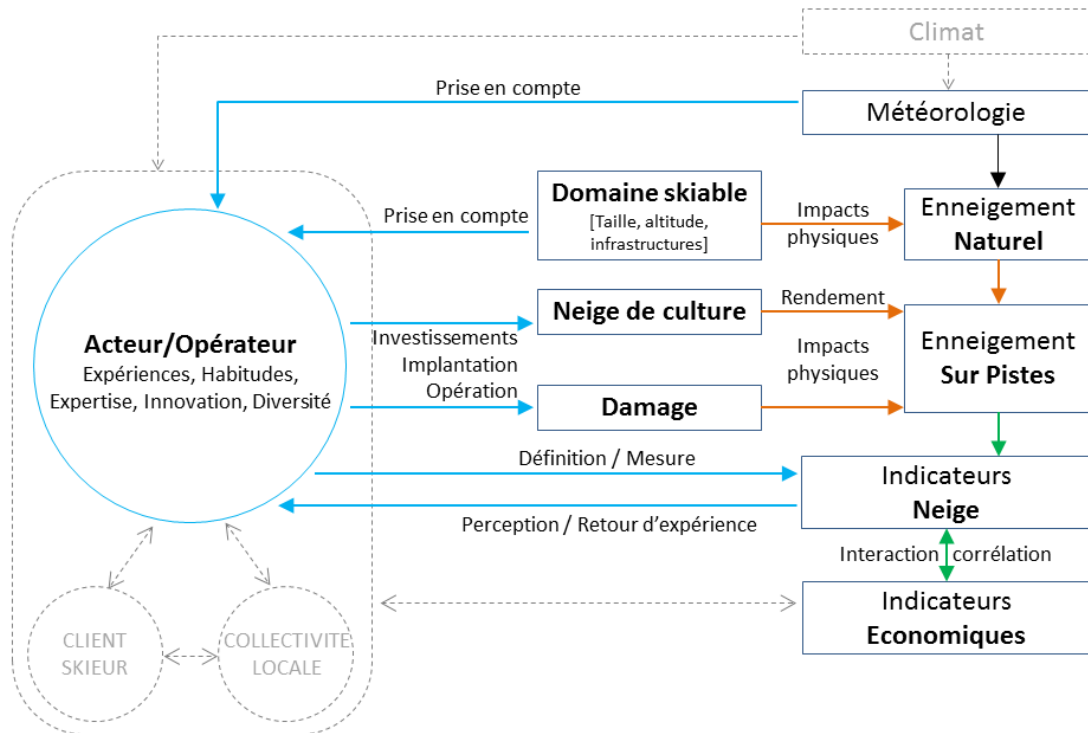


FIGURE 1.2 – Contours de ce travail de thèse. Les interactions bleu correspondent à l’approche professionnelle de la gestion de la neige (Chapitres 2 et 3). Les interactions orange correspondent aux impacts physiques de la gestion de la neige sur les propriétés du manteau neigeux (Chapitres 4 et 5). Les interactions vertes correspondent à l’intégration de ces dimensions pour la détermination d’indicateurs pertinents pour l’étude d’impact de l’enneigement sur l’activité socio-économique des stations de sports d’hiver (Chapitre 6). Les flèches grises correspondent à des interactions d’intérêt pour l’étude des domaines skiables qui ne sont pas prises en compte dans ce travail.

1.2 Variabilité climatique et vulnérabilité économique : introduction et revue de littérature des interactions entre neige, climat et activités de sports d’hiver

Introduction Le ski constitue l’attraction majeure du tourisme hivernal (83% des visiteurs sont pratiquants) loin devant la seconde (la raquette à neige, 16% des visiteurs pratiquants, Lecuret et al. 2014). Cet état de fait incite les opérateurs de domaines skiables à porter une grande attention aux conditions nécessaires à la pratique du ski, notamment l’enneigement, à l’origine de méthodes de gestion de la neige de plus en plus techniques et professionnelles (Fauve et al., 2002). La méthode de damage a été initialement développée aux Etats-Unis (Leich, 2001) pour apporter du confort et de la sécurité

aux pratiquants (Bergstrom and Ekeland, 2004) et améliorer la résistance du manteau neigeux face à l'érosion par les skieurs (Guily, 1991; Fauve et al., 2002) et l'ablation par les processus naturels tels que le vent et la fonte (Keller et al., 2004; Rixen et al., 2004). Emile Allais a été le premier à importer cette méthode en France dans les années 1950 à Courchevel (Vanoise, Alpes). Aujourd'hui, pour autant que nous sachions, toutes les stations dament leurs pistes. Pour autant, le damage ne permet pas de compenser d'éventuels déficits de l'enneigement naturel liés à la variabilité interannuelle du climat et de l'enneigement (Durand et al., 2009a; Beniston, 1997). La vulnérabilité des domaines skiables au déficit d'enneigement est apparue au grand jour à la fin des années 1980 lorsque plusieurs saisons consécutives de faible enneigement sont survenues (Durand et al., 2009b), marquant ainsi le point de départ du développement à grande échelle des équipements en neige de culture en France (Badré et al., 2009). La concurrence entre le marché français du ski et les destinations internationales ou encore avec les activités touristiques alternatives (Morrison and Pickering, 2013) a conduit les opérateurs de domaines skiables à chercher à réduire la dépendance de leur activité aux conditions naturelles d'enneigement grâce à la neige de culture (Hopkins, 2015; Trawöger, 2014). Les opérateurs placent également leur confiance dans l'innovation technologique, soit pour adopter cette méthode là où elle est actuellement absente ou d'intérêt incertain soit pour permettre la production de neige dans des conditions de plus en plus marginales (Hopkins and Maclean, 2014; Hopkins, 2015) sous l'effet du changement climatique (Beniston, 2006; Marke et al., 2014).

L'économie des activités touristiques hivernales a fait l'objet de travaux en conditions passées, actuelles ou projetées du climat en utilisant de nombreux indicateurs tels que les ventes de forfaits de ski (Falk, 2014; Koenig and Abegg, 1997), le nombre de nuitées (Falk, 2010; Töglhofer et al., 2011; Lecuret et al., 2014) ou de produit intérieur brut (Damm et al., 2014; Lecuret et al., 2014). Un défi majeur pour les chercheurs intéressés par la vulnérabilité des activités hivernales face au changement climatique est d'associer ces indicateurs à des variables climatiques telles que la hauteur de neige moyenne (Falk, 2014), le nombre de jours avec de la neige au sol (Töglhofer et al., 2011), ou dépassant un seuil d'épaisseur (Scott et al., 2003; Schmidt et al., 2012; Hanzer et al., 2014; François et al., 2014) ou de masse de neige (Marke et al., 2014). Les difficultés pour combiner de telles approches pluridisciplinaires (Strasser et al., 2014) ou en comparer les résultats (Neuvonen et al., 2015) ont amené la communauté scientifique à établir une règle générique de viabilité aux conditions d'enneigement dite des "100 jours" qui stipule qu'un domaine skiable est viable s'il bénéficie d'une épaisseur de neige d'au moins 30 cm pendant au moins 100 jours (Elsasser et al., 2002; Scott et al., 2003). Cette règle a été employée pour déterminer l'altitude de viabilité de l'enneigement naturel des régions alpines (Elsasser et al., 2002; Abegg et al., 2007), le déclin de la durée de la saison de ski du fait du changement climatique ou encore les quantités de neige de culture requises pour compenser cette diminution de durée (Scott et al., 2003; Steiger, 2010). L'emploi de cette règle dépend cependant d'un seuil d'épaisseur de neige requise qui varie dans la littérature selon la région considérée (Scott and McBoyle, 2007; Pons-Pons et al., 2012) ou la période de la saison (Hennessy et al., 2007; Hanzer et al., 2014; Damm et al., 2014). Néanmoins cette règle a permis d'étudier la viabilité et la capacité d'adaptation de l'industrie du ski au changement climatique par la neige de culture en Australie (Hennessy et al., 2007), Nouvelle-Zélande (Hendrikx and Hreinsson, 2012), Andorre (Pons-Pons et al., 2012), dans les Pyrénées espagnoles et françaises (Pons et al., 2015), en Allemagne (Schmidt et al., 2012), en Suisse (Rixen et al., 2011), en Autriche (Steiger, 2010; Töglhofer et al., 2011; Damm et al., 2014), aux Etats-Unis d'Amérique (Dawson and Scott, 2013) et au Canada (Scott et al., 2003; Scott and McBoyle, 2007). Etonnamment, les Alpes françaises et italiennes sont des régions majeures dans le marché international du ski pour lesquelles très peu d'études ont été réalisées et se limitent à l'analyse des conditions en neige naturelle (Elsasser

et al., 2002; Abegg et al., 2007; Rousselot et al., 2012; François et al., 2014).

Le damage Le damage est une méthode de préparation des pistes de ski aujourd'hui généralisée (Fauve et al., 2002). Le damage modifie significativement les propriétés du manteau neigeux (Keddy, 1979; Fahey et al., 1999; Keller et al., 2004; Rixen et al., 2004; Mossner et al., 2013; Howard and Stull, 2014; De Jong et al., 2015). Fahey et al. (1999) ont suivi quatre pistes damées et mesuré une densité moyenne de la neige supérieure de 36% à la densité de la neige naturelle. Mossner et al. (2013) ont réalisé 344 mesures de densité sur des pistes de ski dont les valeurs allaient de 420 à 620 kg m⁻³ avec une moyenne de 556 kg m⁻³.

La conductivité thermique (Calonne et al., 2011) et la résistance mécanique de la neige (Keller et al., 2004; Howard and Stull, 2014) étant fortement corrélées à la densité de la neige, l'augmentation de la densité de la neige affecte les comportements thermiques et mécaniques du manteau neigeux. Rixen et al. (2004) ont observé dix sites de neige damée et mesuré une différence de - 1°C de la température du sol sous couvert neigeux par rapport aux températures sous un manteau neigeux non damé avec une plus grande fréquence de gel sous couvert neigeux damé. Ces évolutions du comportement thermique du manteau neigeux retardent la date de fonte totale de plusieurs semaines (Rixen et al., 2004; Keller et al., 2004). Par ailleurs, Keller et al. (2004) ont estimé à partir d'observations et de modélisation des conditions de neige damée que la résistance à l'enfoncement de la neige augmente d'un facteur dix lorsque la densité de la neige double, passant de 200 à 400 kg m⁻³.

En résumé, le damage allonge la période de couverture neigeuse et augmente la résistance mécanique du manteau neigeux face à l'érosion par les skieurs (Federolf et al., 2006). Le damage a également un impact bénéfique sur l'accidentologie des pratiquants. Bergstrom and Ekeland (2004) ont conclu à partir du suivi des accidents dans sept stations norvégiennes que la fréquence de damage avait un impact positif sur le nombre d'accidents. Fauve et al. (2002) ont synthétisé l'intérêt du damage sur la base de la littérature et d'entretiens avec des professionnels : les pistes sont rendus plus sûres, plus uniformes (pas de surprises), proposent un bonne "accroche" du ski (pas de glace), sont visuellement attractives et résistent mieux à l'érosion par les skieurs et les conditions météorologiques.

Variabilité, changement climatique et neige de culture Durand et al. (2009b) ont analysé 47 saisons hivernales entre 1958 et 2005 en combinant modélisation et observations et ont démontré une variabilité significative, spatiale et temporelle des conditions d'enneigement dans les Alpes françaises. Cette variabilité est maximale aux altitudes moyennes, autour de 1500 m d'altitude. Des résultats similaires ont été démontrés dans les autres massifs alpins (Gobiet et al., 2014; Beniston, 1997) et en Amérique du Nord (Hughes and Robinson, 1996). La plupart des études d'impact du changement climatique indique que cette variabilité interannuelle va rester significative dans les décennies à venir, quel que soit le scénario d'évolution climatique envisagé (Rousselot et al., 2012; Castebrunet et al., 2014; Kotlarski et al., 2014; Marke et al., 2014).

François et al. (2014) ont étudié les conditions d'enneigement naturel dans les domaines skiables des Alpes françaises sur la période 2001 - 2012, en prenant en compte leurs spécificités géographiques (altitude, pente, orientation) et calculé un indice de viabilité défini comme la fraction du domaine skiable dont l'épaisseur de neige au sol dépasse 30 cm pendant au moins 100 jours. La viabilité moyenne des petites stations s'étale entre 18 et 90% tandis que les très grandes stations ont un indice moyen de 65 à 97%, principalement du fait de leur plus haute altitude. La vulnérabilité des domaines skiables aux conditions d'enneigement naturel a été confirmée pour l'ensemble des pays de l'Arc alpin (Elsasser et al., 2002; Abegg et al., 2007). Falk (2010) a estimé à partir d'un échantillon de 28 stations autrichiennes

sur la période 1986 - 2005 que le nombre de visiteurs diminue lorsque l'épaisseur de neige diminue pour les stations dont l'altitude moyenne se situe en dessous de 2000 m, même si la neige de culture atténue cette baisse de fréquentation. Sur la base d'un grand nombre de domaines skiables autrichiens et sur une longue période de temps (1972 - 2011), Töglhofer et al. (2011) ont conclu qu'une augmentation d'une valeur égale à un écart-type des conditions d'enneigement (combinaison de la hauteur moyenne de neige, de la durée de saison avec neige au sol et avec plus de 30 cm d'épaisseur) conduit à une augmentation de 0.6 à 1.1% du nombre de nuitées dans la station. Comme Falk (2010), cette relation a été établie pour les stations dont l'altitude moyenne est située en dessous de 1800 m d'altitude. Au-delà, une relation négative aux conditions d'enneigement a été établie (Falk, 2010; Töglhofer et al., 2011). Trawöger (2014) a interrogé 24 experts du milieu professionnel dans les Alpes autrichiennes (dirigeants de sociétés de remontées mécaniques, d'offices du tourisme) et conclu que la dépendance aux conditions d'enneigement naturel était le principal moteur du développement des équipements en neige de culture dans les domaines skiables. Hopkins (2015) a tiré les mêmes conclusions d'entretiens de 14 responsables de l'industrie du ski de la région de Queenstown (Nouvelle-Zélande). En 2005, 50% des pistes étaient équipées en neige de culture en Autriche, 18% en Suisse, 16% en France et 40% en Italie (Abegg et al., 2007). En Ecosse, Hopkins and Maclean (2014) ont réalisé des entretiens de responsables dans les cinq domaines skiables de la région et conclu que la production de neige de culture n'était pas viable économiquement en raison de conditions météorologiques inadaptées. Les récents développements des équipements en neige de culture traduisent ainsi une perception confuse et contradictoire du changement climatique par les opérateurs de domaines skiables (Hopkins and Maclean, 2014; Trawöger, 2014). La perception par le monde extra professionnel (grand public, élus) de la vulnérabilité des stations au changement climatique et des conséquences possibles (Dawson and Scott, 2013; Morrison and Pickering, 2012), génère également une stratégie corporatiste vis-à-vis de la neige de culture. D'un côté, les opérateurs de domaines skiables minimisent les risques liés aux déficits d'enneigement naturel (Hopkins and Maclean, 2014), d'un autre côté, ils justifient de nouveaux développements en équipements en mettant en avant la pertinence de la neige de culture pour limiter les effets de la variabilité ou du changement climatique (Morrison and Pickering, 2012; Trawöger, 2014) même si les stations de basse et moyenne altitude restent négativement impactées par les saisons de faible enneigement (Pickering, 2011; Schmidt et al., 2012; François et al., 2014; Francois et al., 2016). Au contraire, l'activité des stations de haute altitude ne montre aucune dépendance (Falk, 2010), voire une dépendance négative à la qualité de l'enneigement (Koenig and Abegg, 1997; Töglhofer et al., 2011), pourtant elles investissent dans des équipements de neige de culture (Falk, 2014) et l'emploient comme argument commercial ("garantie neige", retour ski aux pieds, connexion entre stations). Les leviers pour le développement de la neige de culture dans les domaines skiables demeurent donc très subjectifs et variables d'un site à l'autre (Trawöger, 2014).

Les études d'impact du changement climatique montrent cependant que la durée de la saison de ski va diminuer dans les décennies à venir malgré la neige de culture (Marke et al., 2014) et que la production de neige est une méthode d'adaptation efficace à court voire moyen terme (Pickering, 2011; Schmidt et al., 2012; Morrison and Pickering, 2013) mais s'interrogent sur sa pertinence sur le long terme en raison de son impact sur l'environnement (De Jong et al., 2015), sur le besoin accru en eau (Vanham et al., 2009) et du fait de l'augmentation des coûts de l'énergie (Damm et al., 2014). Hennessy et al. (2007) ont calculé le temps de production disponible et le besoin en neige de culture pour six stations australiennes et conclu que la neige de culture était une solution pertinente jusqu'en 2020 et sans doute insuffisante en 2050, selon le scénario climatique envisagé. Steiger (2010) a étudié l'impact du changement climatique sur trois stations autrichiennes et conclu que leur fonctionnement

serait viable jusqu'en 2040 grâce à la neige de culture. Au-delà, des incertitudes significatives existent, en particulier pour les domaines de basse altitude, malgré la neige de culture. Pons-Pons et al. (2012) ont établi la viabilité de trois stations de haute altitude en Andorre (au-delà de 1900 m) et montré que la neige de culture était une solution viable dans l'hypothèse d'une hausse de température de +2°C mais sans doute pas dans l'hypothèse d'une hausse de +4°C.

La modélisation de la gestion de la neige Les études d'impact du changement climatique sur les conditions d'enneigement qui prennent en compte la production de neige de culture utilisent des schémas généraux pour gérer la production de neige de culture en fonction de conditions optimales à atteindre (Scott et al., 2003; Scott and McBoyle, 2007; Steiger, 2010). Dans la mesure où ces modèles ne sont en général pas capables de prendre en compte les effets liés au damage, les pratiques et équipements de damage ont fait l'objet de très peu d'attention (Guily, 1991; Howard and Stull, 2014). Plusieurs schémas de gestion de la production de neige ont été employés (Scott et al., 2003; Steiger, 2010; Pons-Pons et al., 2012; Hanzer et al., 2014) en travaillant sur la saison entière ou par périodes et en variant les seuils de production : température minimale, épaisseur de neige minimale à produire ou à maintenir. Scott et al. (2003); Scott and McBoyle (2007); Steiger (2010); Pons-Pons et al. (2012) ont utilisé la température de l'air sec pour contrôler la production (seuils de -5°C ou - 2°C) et Rixen et al. (2011) la température du point de rosée (seuil de - 4°C) alors que la variable la plus pertinente utilisée par les nivoculteurs professionnels est la température du thermomètre mouillé T_w , ou température "humide" (Olefs et al., 2010; Hanzer et al., 2014). Le seuil de faisabilité technique aujourd'hui indiqué par les constructeurs est $T_w = - 2°C$ (Olefs et al., 2010; Hanzer et al., 2014) alors que les pratiques des professionnels peuvent être très diverses (Hendrikx and Hreinsson, 2012). L'épaisseur de neige nécessaire à la pratique du ski est fixée à 30 cm par la règle des "100 jours". Cependant, Scott et al. (2003) ont défini une épaisseur de 50 cm pour estimer les quantités de neige de culture nécessaires pour l'activité ski en Ontario, Scott and McBoyle (2007) ont défini l'objectif à 60 cm à Québec et Pons-Pons et al. (2012) à 30 cm en Andorre. Les trois ont défini la saison de production comme la période entre le 22 novembre et le 30 mars. Hennessy et al. (2007) ont divisé la saison hivernale australienne en cinq mois de l'ouverture à la fermeture et défini une épaisseur cible pour chaque mois sur la base d'entretiens avec des opérateurs de domaines skiables (20 cm minimum pour l'ouverture jusqu'à 100 cm en coeur de saison et diminuant jusqu'à 20 cm en fin de saison). D'après Steiger (2010) et Schmidt et al. (2012) en Autriche, une épaisseur minimum de 30 cm doit être produite, constituant une "sous couche" avant de maintenir une épaisseur minimale fixée également à 30 cm, entre le 1^{er} novembre et le 30 mars. De manière similaire Hanzer et al. (2014); Damm et al. (2014) ont défini une période de pré-saison (1^{er} novembre au 15 décembre) au cours de laquelle une "sous-couche" de 30 cm doit être produite avant de maintenir une épaisseur minimale de 60 cm entre le 16 décembre et le 28 février, en Autriche également. A notre connaissance aucune étude n'a porté sur les modes de gestion de la neige de culture des domaines skiables français afin de les situer dans la diversité des approches employées en Andorre, Autriche, Australie, Etats-Unis d'Amérique et Canada.

1.3 Les pratiques professionnelles de gestion de la neige dans les domaines skiables français (Chapitres 2 et 3)

Dans le cadre de cette thèse, une enquête en ligne a été mise à disposition à l'automne 2014 et envoyée à l'attention de 161 contacts d'opérateurs de domaines skiables fournis par l'Association

Nationale des Directeurs de Pistes et de la Sécurité de Stations de Sports d'Hiver (ADSP). Un code unique a été attribué à chacun afin de garantir la confidentialité et un accès personnel. 56 stations ont participé à cette enquête dont 18 le jour de la diffusion de l'information, lors de l'assemblée générale de l'ADSP le 7 octobre 2014. La plupart des participants sont des domaines alpins : 11 des Alpes du Sud¹⁰ et 33 des Alpes du Nord¹¹ dont 21 dans la seule Savoie (73). Huit stations des Pyrénées ont également participé¹², deux du Jura¹³, une du Massif Central¹⁴ et une des Vosges¹⁵.

1.3.1 Caractéristiques des domaines skiables

La base de données socio-économiques "BD Stations" (Marcelpoil et al., 2012) a été utilisée pour traiter les résultats de cette enquête et évaluer la représentativité de cet échantillon dans l'ensemble des domaines français. La "BD stations" contient notamment des données sur les remontées mécaniques des domaines skiables français : leur localisation géographique et des informations quantitatives issues du CAlogue Informatisé des Remontées mécaniques Nationales (CAIRN, fourni par le Service Technique des Remontées Mécaniques et des Transports Guidés - STRMTG), ce qui inclut pour chaque appareil ses altitudes basse et haute, son moment de puissance (produit du dénivelé et du débit théorique, exprimé en km pers h⁻¹). Les données agrégées du moment de puissance des remontées mécaniques (RM) pour chaque station permettent de classer les domaines skiables en quatre catégories (typologie inspirée de celle des Domaines Skiables de France, Table 1.1).

Catégorie de station	Petites stations (S)	Stations moyennes (M)	Grandes stations (L)	Très grandes stations (XL)
Moment de puissance (MP) (km pers h ⁻¹)	MP < 2500	2500 < MP < 5000	5000 < MP < 15000	15000 < MP

TABLE 1.1 – Catégories de stations selon leur moment de puissance employées par (François et al., 2014) et inspirées de Domaines Skiables de France

Les 55 stations de l'échantillon représentent 25% des 220 stations françaises (DSF, 2011). Seules 5% des petites stations sont représentées contre 38% des moyennes, 65% des grandes et 62% des très grandes. Bien que leur nombre est très important, les petites stations ne représentent pourtant qu'une part minoritaire du MP français (7% au niveau national). L'échantillon de 55 stations représente dans son ensemble 51% du moment de puissance français. Des détails supplémentaires peuvent être trouvés dans la section 2.3.3. Cette enquête montre la disparité géographique des domaines skiables en fonction de leur taille. Six des huit très grandes stations participantes sont situées en Savoie et les 16 plus grandes dans les Alpes du Nord. Le MP moyen en Savoie est de 11 400 km pers h⁻¹ et respectivement de 10 500, 5600, 4200 et 4600 km pers h⁻¹ dans le reste des Alpes du Nord, les Alpes du Sud, les Pyrénées et dans les autres massifs français. L'âge moyen des RM en Savoie est de 18.7 ans pour une altitude moyenne de 2110 m. Dans le reste des Alpes du Nord, les Alpes du Sud et les Pyrénées l'âge moyen est de 21 à 22 ans et l'altitude moyenne de 1860 à 2020 m. Les plus grandes stations françaises

10. Départements Alpes-de-Haute-Provence (04), Hautes-Alpes (05), Alpes-Maritimes (06).

11. Départements Isère (38), Savoie (73), Haute-Savoie (74).

12. Départements Ariège (09), Haute-Garonne (31), Pyrénées-Atlantiques (64), Hautes-Pyrénées (65), Pyrénées-Orientales (66) et Andorra.

13. Départements Jura (39).

14. Départements Cantal (15).

15. Département Vosges (88).

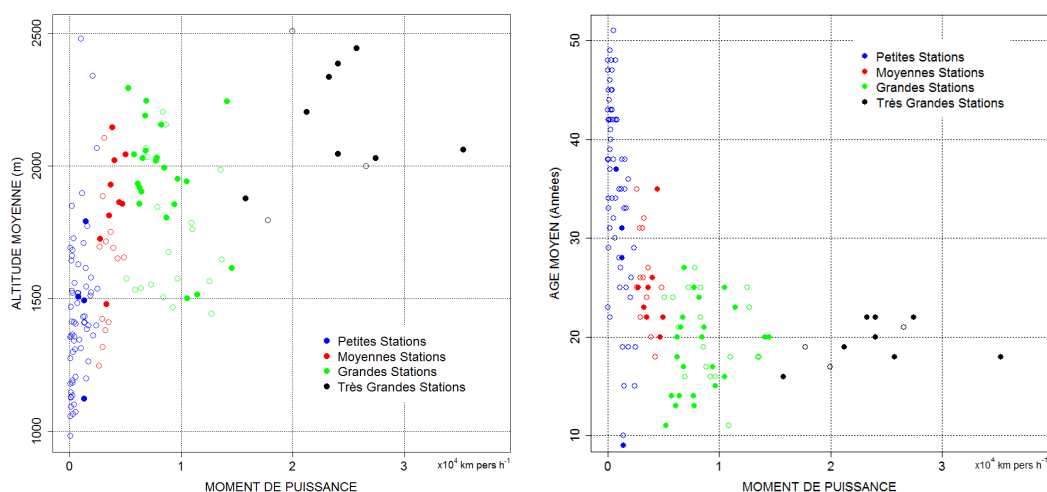


FIGURE 1.3 – a. Altitude moyenne (m) (gauche) et b. Age moyen (droite) des remontées mécaniques des stations participantes (●) et des autres stations des Alpes Françaises (○)

bénéficient donc des RM les plus récentes dans les plus hauts secteurs d'altitude (Figure 1.3) et sont situées d'abord en Savoie puis dans l'ordre dans le reste des Alpes du Nord, les Alpes du Sud et les Pyrénées.

1.3.2 Les priorités des opérateurs de domaines skiables

D'après les résultats de l'enquête, trois priorités générales peuvent être identifiées : satisfaire la clientèle, fournir des solutions techniques pour y parvenir et assurer l'image et la promotion du domaine skiable. La satisfaction des attentes des skieurs est la première priorité : fournir des conditions de ski confortables (note moyenne 9.0/10), permettre le retour ski aux pieds jusqu'au village (8.8/10). Viennent ensuite la contrainte technique de la résistance du manteau neigeux à l'érosion par les skieurs ou les conditions météorologiques (8.2/10) parallèlement au maintien d'une épaisseur suffisante pour garantir l'activité (8.1/10). L'épaisseur minimum à maintenir est homogène entre catégories avec 40 à 50 cm de neige. L'épaisseur requise dépend également de la période de la saison, ce qui montre la prise en compte de l'évolution des conditions dans le temps (Section 2.4.4) avec une épaisseur de 60 cm en coeur d'hiver (février) et une décroissance d'environ 10 cm par mois jusqu'à la fermeture du domaine (Figure 1.4).

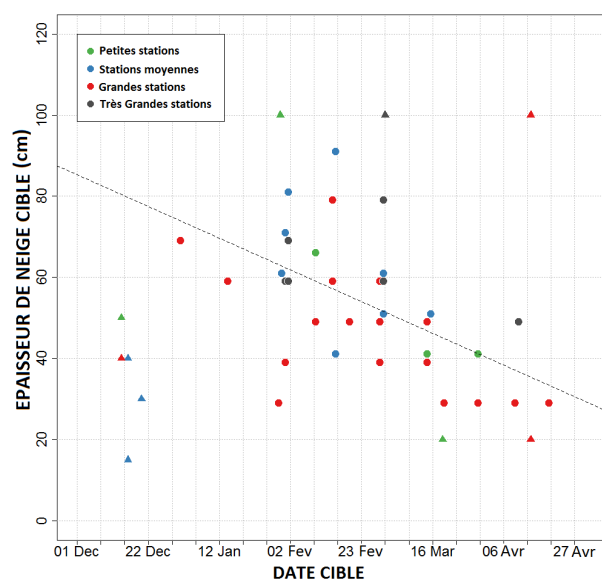


FIGURE 1.4 – Epaisseur de neige à atteindre à un date données selon les stations participantes à l'enquête. Le modèle linéaire ne prend pas en compte les points triangulaires qui correspondent soit à la contrainte d'ouverture (vacances de Noël), soit au minimum ou au maximum des réponses que nous avons retirés (respectivement 20 et 100 cm).

Enfin la promotion du domaine apparaît avec la volonté de proposer des pistes visuellement attractives (8.1/10) et de garantir le lien avec une station par les RM (Section 2.4.2).

Ces objectifs peuvent être réalisés grâce à l'intervention des engins de damage (résistance mécanique, aspect visuel) ce qui conduit les domaines à damer près des deux tiers des pistes chaque jour avec un équipement corrélé avec la surface du domaine : autour de 20 hectares par engin (Section 2.4.3). Dans le cas où l'épaisseur de neige est en deçà des objectifs d'épaisseur de neige cités ci-dessus, la production de neige de culture peut permettre de compenser le manque.

1.3.3 Les moyens associés en neige de culture

Equipements D'après les résultats de l'enquête, l'équipement en neige de culture est similaire aujourd'hui dans les moyennes à très grandes stations avec 30 à 35% des surfaces équipées en neige de culture (Table 1.2). Les grandes à très grandes stations sont cependant celles qui développent le plus leur équipement en neige de culture et devraient être les plus équipées à l'échéance de 2020 (Table 1.2). La vulnérabilité des domaines aux conditions d'enneigement naturel semble être un facteur influant sur le développement de la neige de culture même si elle n'est sans doute qu'un facteur parmi d'autres, et sans doute pas le plus important (Section 2.4.5), ce qui confirme le caractère composite de la stratégie d'équipement. La relation entre le taux d'équipement et la vulnérabilité des domaines à l'enneigement naturel (François et al., 2014) est assez faible (Section 2.4.5, Figure 1.5). Pourtant, l'indice de viabilité calculé par François et al. (2014) à l'enneigement naturel est respectivement de 83% et 65% dans les Alpes du Nord et les Alpes du Sud sur la période 2001 - 2012, avec des surfaces équipées en enneigeurs respectivement de 32% et 41%.

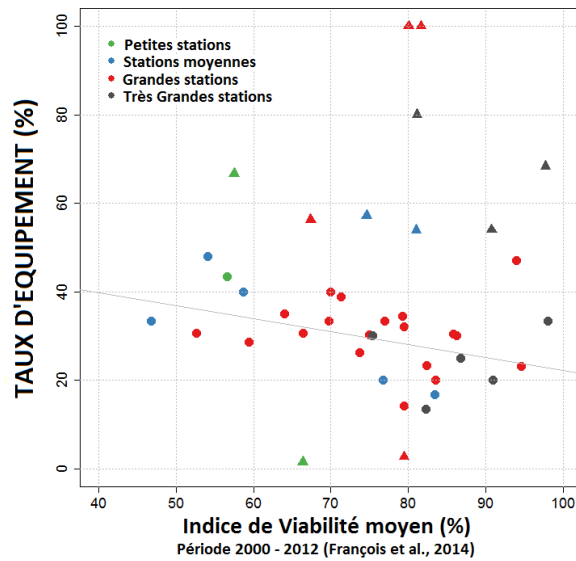


FIGURE 1.5 – Taux d'équipement en fonction de l'indice de viabilité en neige naturelle (%) d'après François et al. (2014) pour les stations participantes à l'enquête (période 2001 - 2012). Le modèle linéaire ne prend pas en compte les points triangulaires qui excèdent 50% ou sont inférieurs à 10% de surface équipée en enneigeurs.

Catégorie de station	Petites stations (S)	Stations moyennes (M)	Grandes stations (L)	Très grandes stations (XL)
Surface de piste équipée en neige de culture (%)	18 ± 25	34 ± 16	35 ± 21	34 ± 24
Capacité actuelle des retenues par hectare de piste équipée (m³ ha⁻¹)	1450 ± 2350	1800 ± 1650	1700 ± 1600	1500 ± 1300
Extension prévue des équipements en enneigeurs ? Ont répondu "Oui" (%)	71	57	88	100
Surface équipée en 2020 (%)	34 ± 32	39 ± 17	47 ± 46	49 ± 38

TABLE 1.2 – Equipements actuels et à l'horizon 2020 en neige de culture (± écart-type).

D'après les résultats de l'enquête, les retenues d'altitude sont la première source d'approvisionnement en eau pour la production de neige : une station sur trois n'a que cette seule ressource en eau et la plupart y ont recours en association avec les réseaux d'eau potable ou les cours d'eau naturels. La capacité est liée à la surface équipée en neige de culture : 1500 à 1800 m³ par hectare de piste équipée, 1900 m³ par hectare en moyenne pour les stations qui n'ont que la retenue comme source d'approvisionnement. Ces capacités correspondent à une épaisseur de neige de culture de 38 à 48 cm avec une densité de 400 kg m⁻³ (Hanzer et al., 2014).

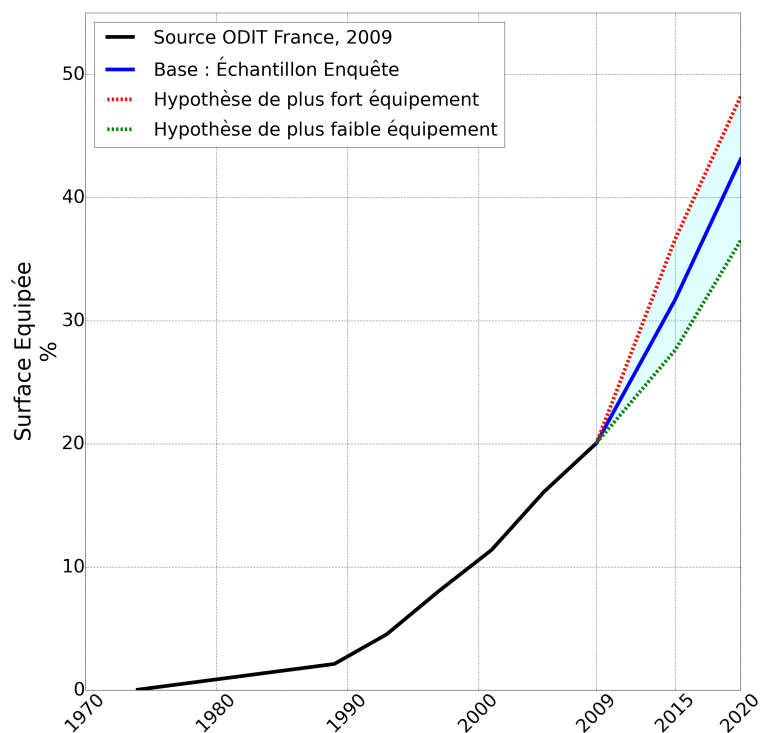


FIGURE 1.6 – Evolution des surface équipées en neige de culture depuis 1970 dans les Alpes françaises et projections jusqu'en 2020 (Spandre et al., 2015).

Distribution des enneigeurs au sein du domaine D'après les résultats de l'enquête, plus les stations sont petites, plus leur attention à la distribution des enneigeurs est grande : près des deux tiers des petites et moyennes stations indiquent installer leurs enneigeurs en deçà d'une certaine altitude contre seulement une très grande station sur quatre. Trente stations (sur 54) ont indiqué une altitude maximum pour leurs enneigeurs qui se trouve fortement corrélée et à peine supérieure à l'altitude moyenne des remontées mécaniques. Les orientations préférentielles pour l'installation d'enneigeurs n'ont pas permis de dégager de tendance, la plupart des domaines indiquant que leurs enneigeurs étaient disposés "au dessus du village". Ces éléments combinés s'expliquent sans doute par la volonté de garantir le retour skis aux pieds jusqu'au front de neige du domaine. Parallèlement, l'intérêt plus faible pour le positionnement des enneigeurs aux faibles altitudes avec la taille des stations pourrait s'expliquer par l'attention croissante que celles-ci portent aux connexions avec des secteurs d'altitude (glacier) ou avec des domaines voisins. Ces connexions sont faites le plus souvent par des crêtes d'altitude et incitent sans doute l'équipement des pistes de liaison qui se situent en altitude (Table 2.5).

Evolutions D'après les résultats de notre enquête, environ 43% des pistes devraient être équipées en neige de culture à l'horizon 2020 et près de 50% dans les très grandes stations. La corrélation du nombre d'enneigeurs (Table 2.3) et de la capacité des retenues d'eau (Table 1.2) à la surface de pistes équipées suggère que ces équipements évolueront dans des proportions identiques avec des demandes en eau et en énergie elles aussi proportionnelles. Ces évolutions s'accompagneront sans doute d'une évolution du prix du forfait du fait des investissements initiaux et des coûts de fonctionnement proportionnels également accompagnés des hausses probables des prix de l'énergie (Töglhofer et al., 2011; Damm et al., 2014).

1.3.4 Pistes d'approfondissement et d'exploitation

Ces éléments soulèvent l'intérêt pour l'étude des caractéristiques des stations qui ne soit plus seulement basée sur leur taille mais prenant également en compte la relation spatiale entre remontées mécaniques, neige de culture et immobilier de stations d'une part, et d'autre part, entre la localisation d'une station par rapport aux plus proches centres urbains, sa clientèle cible et les concurrents directs du domaine. Ces interactions permettraient sans doute d'améliorer la compréhension station par station de la flexibilité, des modes de consommation et de la perception de la neige de culture par la clientèle et ses exigences en termes de garantie neige et capacités à évoluer vers des produits plus coûteux avec en conséquence des développements en infrastructures de neige de culture (entre autres) très divers. Dans ce cadre, le mode de gestion des domaines (privé, public ou mixte) est une variable à prendre en compte, notamment dans la perspective du développement des territoires de montagne dans un contexte de changement climatique. La concurrence directe (locale ou internationale) pourrait elle avoir un impact fort sur la recherche de spécificités et d'arguments de vente par les domaines skiables, dont la neige de culture constituerait un élément central, en particulier pour le marché des grands hébergeurs et la gestion de leur catalogue d'offres.

Cette enquête fournit cependant des éléments suffisants pour la conduite d'études de vulnérabilité des domaines skiables aux conditions d'enneigement qui prennent en compte leurs méthodes de gestion (damage, production de neige). De telles études nécessitent des outils de modélisation objectifs et robustes pour la mise en commun d'informations météorologiques, nivologiques, géographiques et sur la gestion humaine de la ressource neige. L'association de données géographiques sur les domaines skiables a été décrite par François et al. (2014) à l'origine d'une chaîne de modélisation semi distribuée nivo-météorologique des conditions d'enneigement naturel dans les domaines skiables des Alpes françaises. Cette chaîne a été complétée dans le cadre de cette thèse par l'implémentation des impacts du damage et de la production de neige sur l'évolution simulée du manteau neigeux pour permettre la prise en compte de l'action de l'homme sur l'évolution des conditions de neige en stations. Ces évolutions de la partie nivo-météorologique de cette chaîne de modélisation sont décrites dans la section suivante.

1.4 Observation et modélisation des conditions d'enneigement sur pistes de ski (Chapitres 4 et 5)

Les méthodes de gestion de la neige modifient significativement l'état physique et le comportement thermique et mécanique du manteau neigeux (Guily, 1991; Fauve et al., 2002) avec pour conséquence une divergence parfois très marquée des conditions d'enneigement sur la piste de ski et dans son environnement immédiat (Fahey et al., 1999; Rixen et al., 2001). Sous l'action de processus naturels ou par une action supplémentaire par l'homme, la neige subit en permanence des transformations physiques gouvernées par les conditions atmosphériques (Armstrong and Brun, 2008) en interaction avec les propriétés physiques internes au manteau neigeux qui influencent le bilan d'énergie et par conséquent leur propre évolution (Brun et al., 1992; Vionnet et al., 2012). Du fait des nombreux comportements non linéaires du manteau neigeux, l'appréhension des conditions d'enneigement dans les domaines skiables nécessite une méthode capable de prendre en compte simultanément ces processus physiques et les actions humaines de gestion de la neige.

Dans le but de construire un outil capable de prendre en compte les impacts physiques de la gestion de la neige sur les conditions d'enneigement d'une piste de ski, nous avons explicitement intégré des approches les plus exhaustives possibles du damage et de la neige de culture dans le modèle détaillé

Crocus (Vionnet et al., 2012). Le damage et la production de neige ont été implémentés sur la base de la littérature sur le sujet et d'entretiens avec des professionnels. Ces derniers ont été impliqués dans le développement d'un schéma simulant les pratiques de gestion de neige le plus fidèlement possible. Les sorties de ce modèle ont été évaluées à l'aide d'observations de la hauteur de neige, de l'équivalent en eau et de profils stratigraphiques réalisées dans quatre stations des Alpes françaises (Autrans, Chamrousse, Les Deux Alpes, Tignes) au cours des hivers 2014 - 2015 et 2015 - 2016, couvrant une large gamme d'altitudes, de taille de domaines et de conditions météorologiques. La diversité des approches de ces quatre stations ainsi que la confrontation entre deux saisons successives ont permis le développement d'un outil générique capable de travailler sur un éventail le plus large possible de domaines skiables. Ces observations ainsi que les développements du modèle numérique sont décrits en détail dans le chapitre 4.

1.4.1 Développement d'un modèle numérique de simulation des effets du damage et de la production de neige sur l'évolution saisonnière du manteau neigeux (Chapitre 4)

La chaîne de modélisation SAFRAN - Crocus Le modèle physique multi couches d'évolution du manteau neigeux SURFEX/ISBA-Crocus (par la suite, Crocus ; Vionnet et al. (2012)) établit les bilans d'énergie et de masse du manteau neigeux par la résolution d'équations physiques sous jacentes. Les processus simulés incluent les phénomènes internes tels que le changement de phase, la percolation d'eau liquide, la densification et l'évolution de la structure microscopique de la neige avec leurs effets respectifs sur les propriétés thermiques et radiatives du manteau neigeux. Le bilan d'énergie est réalisé aux deux interfaces du manteau neigeux avec l'atmosphère et le sol et sur son profil vertical (modèle uni-dimensionnel) discrétisé en maximum 50 couches de neige distinctes, avec un pas de temps d'un quart d'heure. Les propriétés physiques des couches de neige reposent notamment sur les variables suivantes :

- la masse volumique (ρ , couramment appelée "densité") : le rapport entre la masse d'un échantillon de neige et son volume, en kg m^{-3} (Vionnet et al., 2012) ;
- la surface spécifique de la neige (SSA) : le rapport entre la surface totale de l'interface glace - air d'un échantillon de neige et sa masse totale, en $\text{m}^2 \text{kg}^{-1}$ (Carmagnola et al., 2014) ;
- la sphéricité (S) : la proportion de formes arrondies et de formes anguleuses (Brun et al., 1992) ;
- l'âge : le nombre de jours depuis la chute de neige à l'origine de la couche considérée, utilisé pour déterminer le taux d'impuretés déposées dans la couche de neige (Vionnet et al., 2012)

Le système météorologique SAFRAN Dans les zones de montagnes françaises, Crocus est généralement utilisé en association avec le Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige (SAFRAN) (Durand et al., 1993). SAFRAN opère à une échelle dite de "massifs" au sein desquels les conditions météorologiques sont supposés homogènes et ne dépendre que de l'altitude et des caractéristiques du point considéré (pente, orientation). Les données météorologiques sont fournies par pas altitudinal de 300 m (de 600 à 3600 m maximum) et à une résolution horaire. SAFRAN est un modèle de descente d'échelle et d'assimilation de données issues de modèles numériques du temps à grande échelle, d'observations de surface (stations automatiques dont Nivôses, observations manuelles notamment du réseau d'observateurs nivo-météorologiques) et de radiosondes dont la base de données couvre les 57 ans de 1958 à aujourd'hui (Durand et al., 2009b). SAFRAN reste dépendant de modèle de grande échelle et de réseaux d'observations qui ont évolué depuis leur création (en particulier de-

puis 1980), ce qui constitue une source de variabilité dans le temps et dans l'espace (Vidal et al., 2010). Malgré ces incertitudes, SAFRAN est un outil pertinent pour le monde de la recherche et a déjà été employé dans un grand nombre d'études dans les Alpes françaises (Martin et al., 1994; Gerbaux et al., 2005; Durand et al., 2009b; Lafaysse et al., 2011). Les activités opérationnelles et de recherches réalisées jusqu'ici ont apporté la preuve à de nombreuses reprises que l'association du système SAFRAN et du modèle Crocus fournit des informations pertinentes et réalistes des conditions d'enneigement dans les massifs français (Essery et al., 1999; Rousselot et al., 2010; Durand et al., 2009b). Toutes les simulations présentées dans ce travail reposent sur les données météorologiques de SAFRAN correspondant à chaque site d'observation (altitude, pente et orientation exactes). Nous avons analysé de manière spécifique les conditions fournies par SAFRAN avec les données in-situ des conditions atmosphériques (température, humidité) et de neige naturelle (réseau d'observateurs nivo-météo, stations automatiques). Le cas échéant, nous avons adapté la phase des précipitations (associée à la limite pluie neige) et leur quantité, toutes les deux très variables spatialement afin de correspondre au mieux aux conditions atmosphériques locales. Nous avons également pris en compte l'environnement immédiat des sites pour simuler les effets d'ombre associés à des reliefs marqués. La hauteur angulaire de l'horizon a été déterminée par une méthode S.I.G¹⁶ et contrôlée sur le terrain.

Approche numérique du damage Un engin de damage est principalement composé de trois outils : la lame, la chenille et la fraise. La lame déplace des volumes de neige (bien qu'ayant sans doute d'autres effets), la chenille permet la progression de l'engin et transfère son poids au manteau neigeux et la fraise agit comme une sorte de mixeur sur les couches de surface (Figure 1.7). Dans la mesure où le modèle Crocus est uni-dimensionnel selon la verticale, il ne peut en l'état actuel prendre en compte des effets de déplacements horizontaux de neige. Tout effet associé à la lame n'est pas pris en compte dans cette étude.



FIGURE 1.7 – La fraise est un outil monté à l'arrière de l'engin de damage constitué d'un arbre principal animé d'un mouvement de rotation surmonté de rangées de dents qui agissent comme un mixeur pour les couches de surface du manteau neigeux.

L'effet de la chenille a été modélisé comme un poids statique et constant d'une valeur de 500 kg m^{-2} appliqué à la surface du manteau neigeux (Guily, 1991; Olefs and Lehning, 2010; Howard and Stull, 2014). Ce poids statique est appliqué sur les premières couches de neige sans effet d'amortissement jusqu'à 50 kg m^{-2} de profondeur i.e. 50 cm de neige à 100 kg m^{-3} , puis est amorti avec la profondeur dans le manteau neigeux entre 50 kg m^{-2} et 150 kg m^{-2} i.e. entre 50 et 150 cm de neige à 100 kg m^{-3} .

16. Système d'Information Géographique.

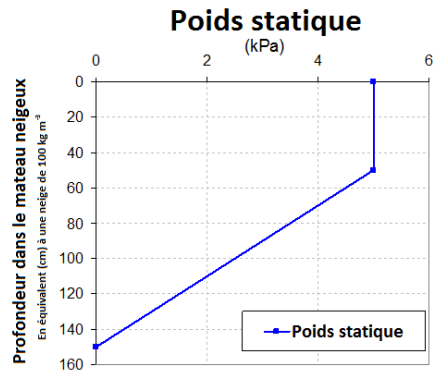


FIGURE 1.8 – Poids statique appliqué sur le manteau neigeux dans le modèle SAFRAN - Crocus-Resort

m^{-3} (Figure 1.8).

La fraise est un arbre à cames fixé à l'arrière d'un engin de damage et entraîné en rotation selon un axe parallèle au plan horizontal. Lorsqu'il est positionné en appui sur le manteau, cet outil applique une pression supplémentaire au poids de l'engin et agit comme un mixeur pour les couches de surface de la neige (Fauve et al., 2002; Guily, 1991; Keddy, 1979). Par conséquent la fraise agit sur la densité et les propriétés (sphéricité, SSA, âge) de la neige de surface. La modélisation numérique de l'action de la fraise proposée dans cette étude se fait en plusieurs temps par homogénéisation puis évolution des propriétés (Figure 1.9) :

- Les couches de surface sont sélectionnées jusqu'à 35 kg m^{-2} de profondeur (35 cm de neige à 100 kg m^{-3} ou 7 cm de neige à 500 kg m^{-3}) ;
- Les propriétés moyennes des couches sélectionnées (densité, sphéricité, SSA, âge) sont calculées en pondérant les propriétés de chacune par sa masse ;
- Les propriétés moyennes sont modifiées (voir ci-dessous) et ré attribuées à chaque couche ;
- La hauteur de chaque couche est recalculée en fonction de sa masse volumique afin de respecter la conservation de masse de chaque couche.

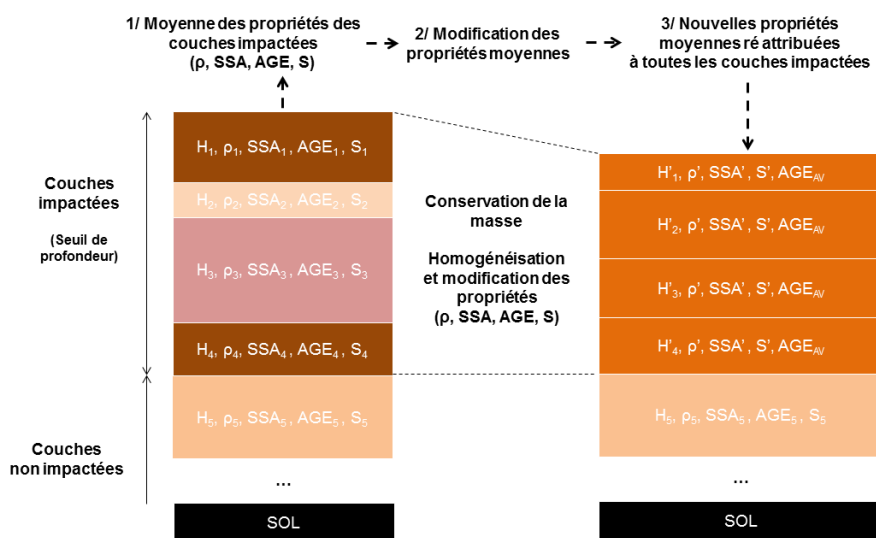


FIGURE 1.9 – L'approche numérique du damage dans Crocus

L'âge des couches de neige est homogénéisé mais pas modifié. Pour les autres variables, la modification des propriétés des couches de neige se fait de manière progressive vers des propriétés observées de neige naturelle damée (Keddy, 1979; Guily, 1991) correspondant à des grains fins de petite taille (0.3 mm, SSA = 25 m² kg⁻¹), très arrondis (sphéricité de 90%) et de densité 450 kg m⁻³. Le détail de cette méthode est décrit dans la section 4.2.3. La fréquence, les horaires et les contraintes liés au damage ont été déduits des échanges avec les professionnels et synthétisés sous la forme d'un schéma décisionnel menant à l'action de damage dans le modèle (Figure 1.10). L'action a lieu si l'ensemble des points suivants sont vrais :

- Période de damage : du 1^{er} novembre à la fermeture de la station ;
- Une quantité minimum de neige est nécessaire pour permettre le damage : 20 kg m⁻² soit 20 cm de neige récente à 100 kg m⁻³ ;
- Le créneau horaire est 20h - 21h chaque jour (par défaut). Si une chute de neige a eu lieu dans la nuit, le damage est possible entre 6h et 9h le matin.

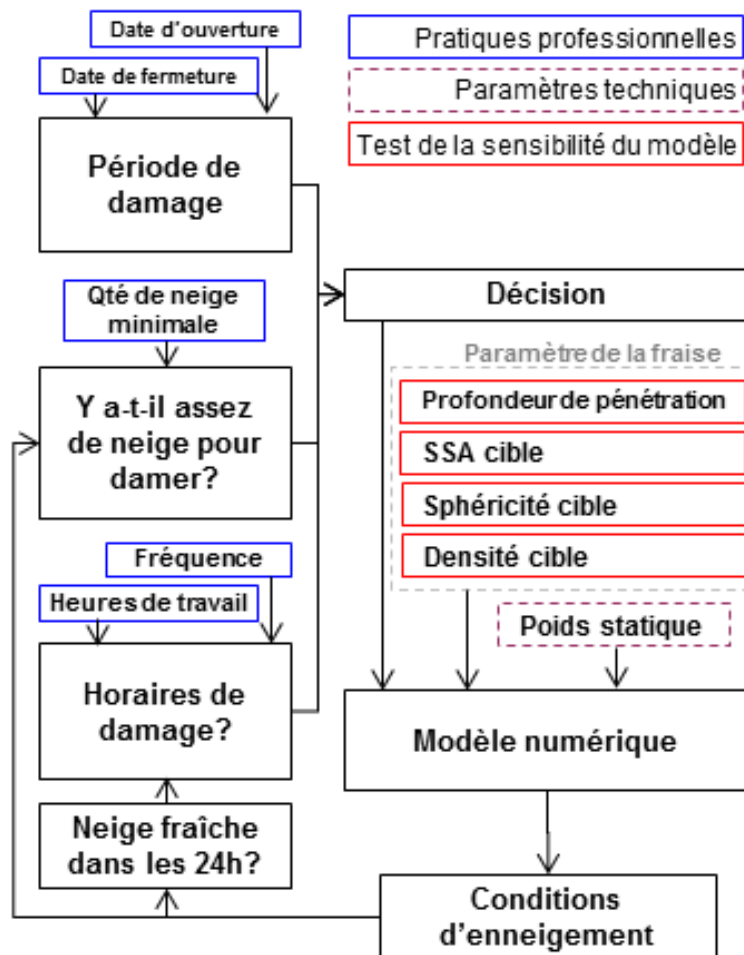


FIGURE 1.10 – Schéma du damage implanté dans Crocus

Approche numérique de la production de neige de culture Le but de cette section est de décrire l'implémentation d'un module physique de production de neige de culture dans le modèle Crocus et d'en évaluer la pertinence. Pour ce faire, nous avons travaillé sur les données de production réelles des sites d'observations (volumes d'eau, répartition dans la saison) que nous avons utilisées comme

objectif de production dans le modèle afin d'en évaluer la capacité à reproduire les conditions observées à partir du moment où les quantités de neige produites sont cohérentes (Table 4.2). La masse de neige produite par unité de surface a été déduite du volume d'eau employé (m^3 d'eau, converti en kg) et de la surface d'étalement de cette neige (m^2) avec une incertitude associée. Un taux d'efficacité (%) supposé représenter la fraction utile du volume d'eau employé pour la production (une fois les pertes éventuelles déduites) a été utilisé et testé (Section 4.2.4).

Les paramètres physiques de la neige de culture dans le modèle (Section 4.2.4) correspondent à de petits grains ronds de 0.3 mm de diamètre ($SSA_{MM}=22 \text{ m}^2 \text{ kg}^{-1}$), quasi sphériques (sphéricité 90%) et de densité élevée $\rho_{MM}=600 \text{ kg m}^{-3}$. Si la production a lieu tandis qu'une précipitation naturelle a également lieu, les propriétés de la neige précipitées sont pondérées par leur taux massique de précipitation respectif ($\text{kg m}^{-2} \text{ s}^{-1}$). De manière similaire au damage, un schéma décisionnel a été implémenté pour intégrer l'ensemble des éléments menant à la production de neige (Figure 1.11), sur la base d'entretiens avec des nivoculteurs et de précédents travaux sur ces questions (Hanzer et al., 2014; Marke et al., 2014). La production est possible du 1^{er} novembre au 31 mars, entre 19h et 8h le lendemain matin. Chaque soir à 19h, le cumul de production jusqu'à date est comparé avec l'objectif de production. Si l'état est déficitaire, la production est possible pendant toute la nuit. Si excédentaire, aucune production ne peut avoir lieu.

Les conditions météorologiques sont également prises en compte : le vent ne doit pas excéder 4.2 m s^{-1} (15 km h^{-1}) et la température humide (T_W) doit être inférieure à un seuil prescrit. La température humide ou température du thermomètre mouillé semble être le critère le plus pertinent pour gérer la production de neige (Olefs et al., 2010) dont la valeur exacte ne peut être obtenue que par itérations successives. Par simplicité, nous avons implémenté une méthode explicite tirée des travaux de Jensen et al. (1990) pour calculer T_W à partir des données SAFRAN de température sèche et d'humidité de l'air. Cette méthode fournit des valeurs cohérentes de la température humide pour des températures sèches entre -15 et 0°C et des humidités relatives entre 30 à 100% : l'écart maximum aux résultats de la méthode itérative de Olefs et al. (2010) est $\pm 0.3^\circ\text{C}$.

Enfin, nous prenons en compte un taux de conversion de la masse d'eau utilisée pour la production et la masse de neige effective sur la piste, entendu qu'une fraction de cette masse d'eau est perdue, soit par des processus thermodynamiques de sublimation ou d'évaporation (Eisel et al., 1988, 1990; Hanzer et al., 2014), soit par des processus mécaniques tels que la suspension et transport par le vent au-delà des limites de pistes (Olefs et al., 2010). Dans cette section nous considérons 4 niveaux de conversion entre 100% (aucune perte) à 25 % (75% de perte) avec l'utilisation d'un taux de 50% par défaut.

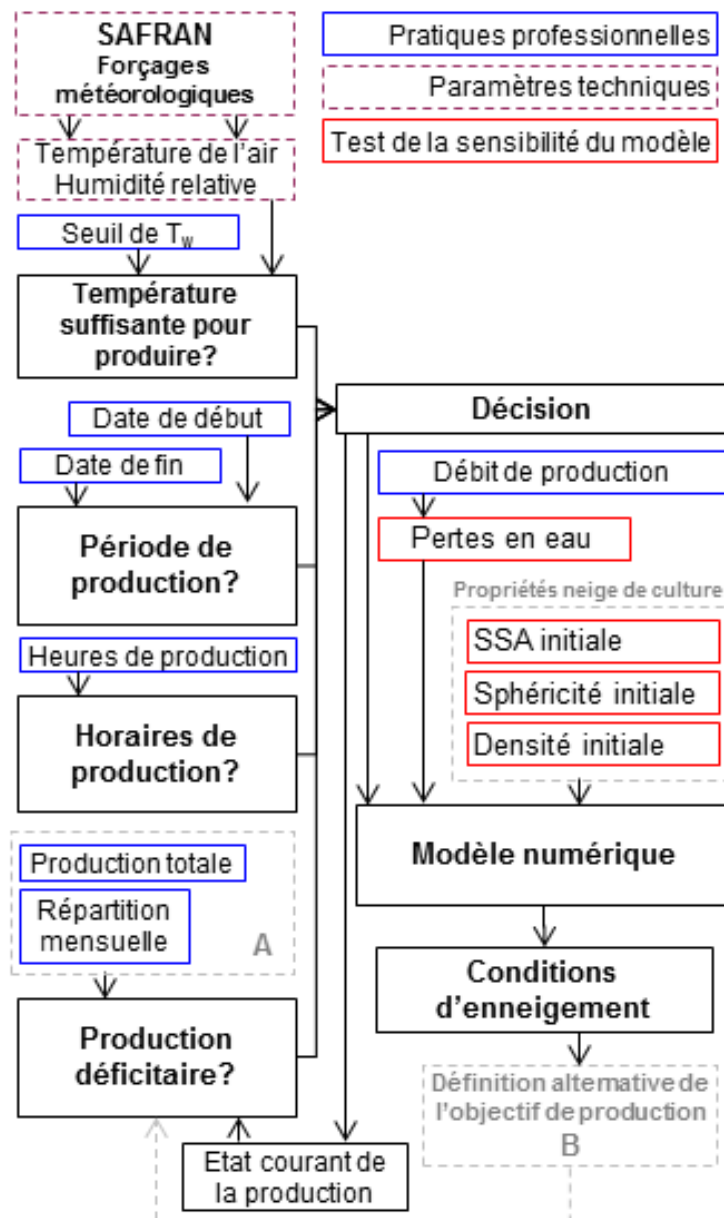


FIGURE 1.11 – Schéma décisionnel pour la production de neige de culture implémenté dans Crocus

1.4.2 Confrontation aux observations des sorties de modèle

Observations in-situ Les équipes de pisteurs de quatre domaines skiables des Alpes du Nord (Tignes, Chamrousse, Autrans et Les 2 Alpes) nous ont aidé à réaliser des observations au cours des hivers 2014 - 2015 et 2015 - 2016 (Table 4.1, Figure 1.12), couvrant une gamme de conditions météorologiques, de pratiques et d'habitudes de gestion de la neige la plus large possible. Trois sites les plus proches possibles les uns des autres ont été sélectionnés pour chaque station : en neige naturelle (référence), en neige naturelle damée et en neige naturelle et de culture damées.

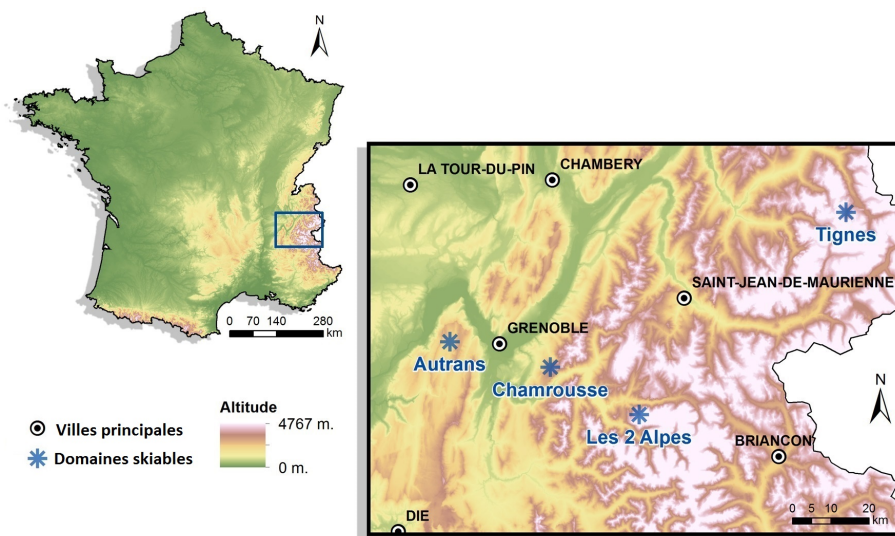


FIGURE 1.12 – Situation géographique des quatre stations partenaires autour de Grenoble (France) : Tignes (Haute-Tarentaise), Chamrousse (Belledonne), Autrans (Vercors) et Les 2 Alpes (Oisans).

Les volumes d'eau utilisés pour la production de neige nous ont été communiqués par les nivoculteurs et les surfaces d'étalement de la neige (Table 4.2) ont été déterminées à partir de l'implantation des enneigeurs, des limites physiques de la piste (ravin, arbres) et des observations et discussions avec les pisteurs. Une incertitude a été déterminée pour chaque site qui apparaît comme une enveloppe autour des tracés des simulations (Section 4.5) pour rendre compte de l'erreur associée.

Les observations de hauteur de neige ont été réalisées chaque semaine par les équipes de pisteurs à l'aide d'une perche à neige. Chaque mois nous avons réalisé un relevé de l'équivalent en eau (masse de neige en kg m^{-2} de piste), de la densité moyenne du manteau neigeux et du profil stratigraphique. Préliminaire essentiel à l'étude d'impact de la gestion de neige sur les propriétés du manteau neigeux, la modélisation de la neige naturelle comporte elle aussi une erreur qu'il convient d'évaluer. La Figure 1.13 expose les conditions d'enneigement naturel pour les quatre sites expérimentaux avec les observations réalisées, les simulations alimentées par des forçages SAFRAN avant et après modifications. La chaîne SAFRAN-Crocus montre ici qu'elle fournit des simulations pertinentes de la neige naturelle avec des erreurs (Table 4.5) de l'ordre de 30 kg m^{-2} sur l'équivalent en eau et 10 cm sur l'épaisseur de neige après modification des forçages. Par la suite toutes les simulations ont été réalisées avec ces forçages modifiés.

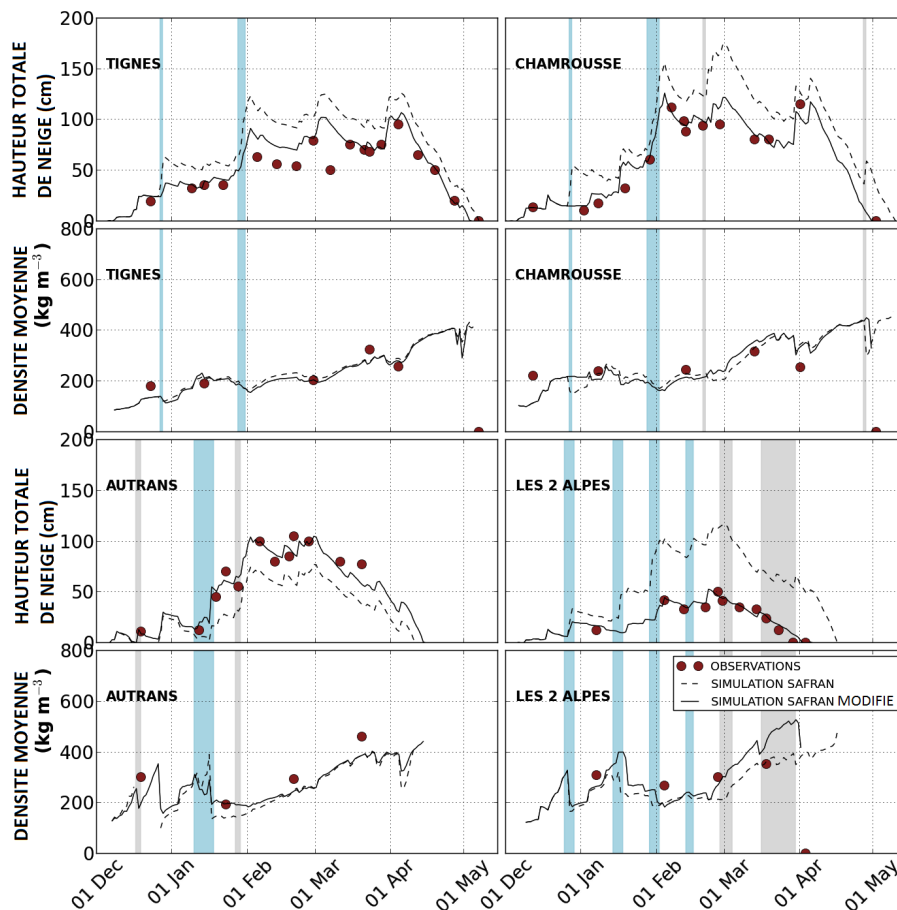


FIGURE 1.13 – Hauteur totale de neige naturelle et densité moyenne du manteau neigeux et données observées en 2014 - 2015. Les simulations utilisant les données météorologiques de SAFRAN sans corrections (pointillés) et avec corrections (trait plein) sont présentées (Section 5.2.4). En bleu les évènements pour lesquels la quantité de précipitations a été modifiée et en gris les évènements pour lesquels la phase des précipitations (limite pluie/neige) a été modifiée.

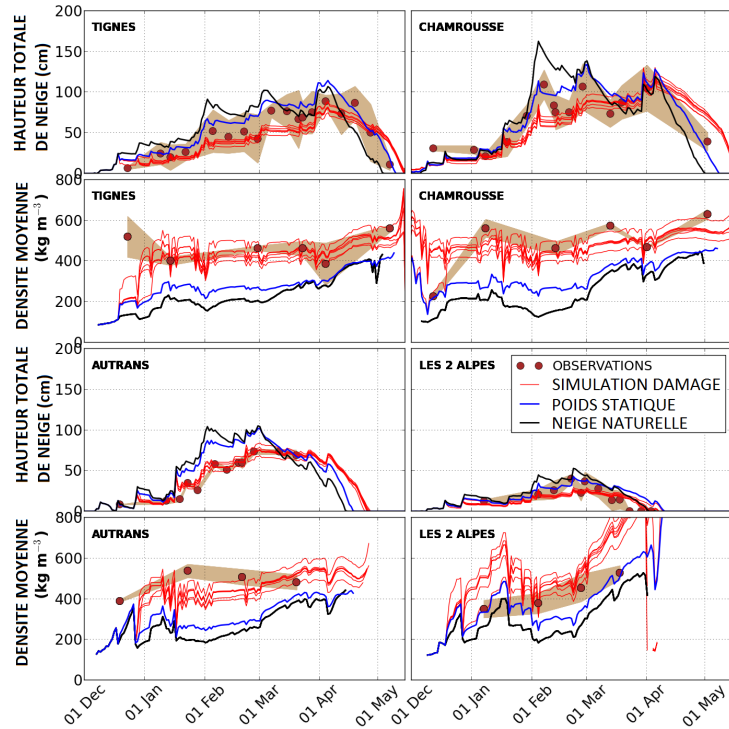


FIGURE 1.14 – Impact du damage observé sur les propriétés du manteau neigeux (densité moyenne, hauteur de neige). Les simulations par les sept configurations du modèle sont présentées (Table 4.3 et 4.4) ainsi que les simulations réalisées en prenant en compte le poids statique uniquement (pas de fraisage) et les conditions d’enneigement naturel. L’enveloppe brune correspond à \pm l’écart-type des observations réalisées autour de la valeur moyenne.

Evaluation de la modélisation numérique du damage Les simulations des conditions d’enneigement naturel damé (sans production) sont accompagnées des observations des quatre sites expérimentaux sur la Figure 1.14. Les écarts aux observations sont détaillés dans la Table 4.6. Le modèle fournit des conditions d’enneigement fiables au regard des observations en neige naturelle damée, notamment en termes de densité moyenne (400 à 500 kg m^{-3}). Les profils de densité et de surface spécifique des 30 premiers cm de neige simulés par le modèle ont également été comparés aux observations (Figure 1.15) avec là aussi une bonne cohérence. Ces observations permettent dans l’ensemble de conclure à la capacité du modèle à reproduire fidèlement les propriétés du manteau neigeux damé (densité, surface spécifique).

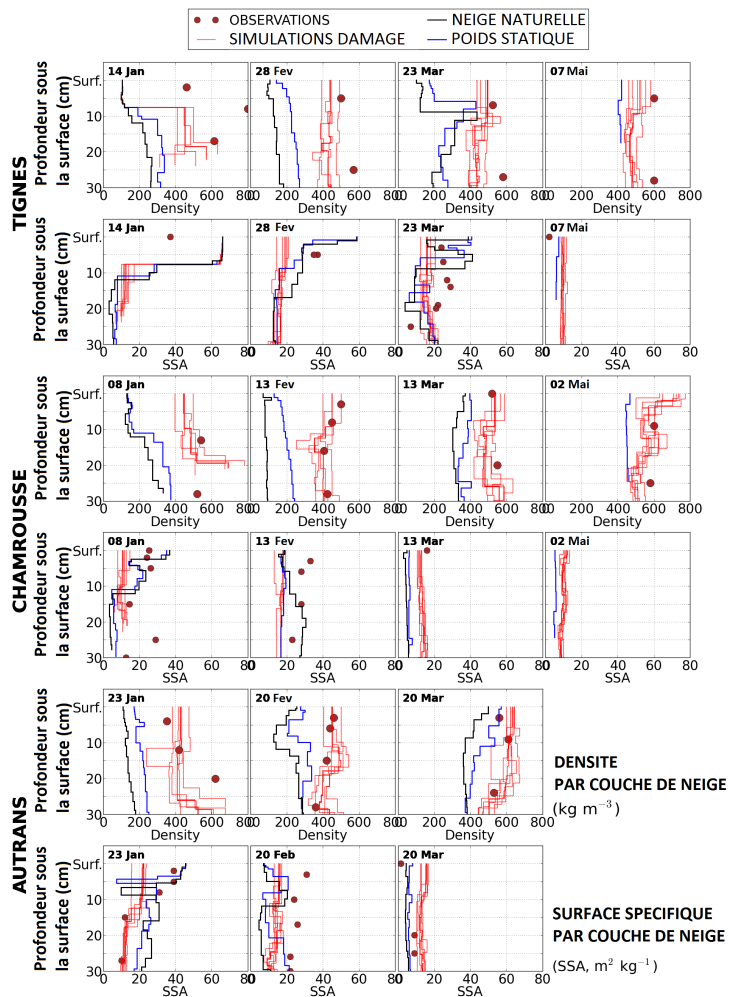


FIGURE 1.15 – Impact du damage observé sur les propriétés des 30 cm de surface du manteau neigeux (densité, microstructure). Les simulations par les sept configurations du modèle sont présentées (Table 4.3 et 4.4) ainsi que les simulations réalisées en prenant en compte le poids statique uniquement (pas de fraissage) et les conditions d’enneigement naturel.

Des observations de la température de la couche de neige au contact du sol ont également été réalisées au cours de l’hiver 2015 - 2016 à Autrans dans les mêmes conditions qu’en 2014 - 2015 (Section 4.7). La température a été observée du 21 novembre 2015 au 10 mai 2016 avec des capteurs autonomes de températures à un pas de temps de 2 h. La température observée sous manteau neigeux naturel était en moyenne de - 0.1°C avec des épisodes de gel (températures négatives du sol) pendant 20% du temps environ. Sous manteau neigeux damé, cette température moyenne s’abaisse à - 0.9°C avec des températures négatives près de 70% du temps, soit une différence de - 0.8°C sur la saison, ce qui est conforme avec des observations par Rixen et al. (2004). Les simulations ont fourni des informations très cohérentes avec une température moyenne simulée sous manteau neigeux naturel de - 0.01°C et - 1.04°C sous manteau damé (70% du temps avec une température de sol négative également). La prise en compte des effets du damage notamment sur la densité de la neige montre la capacité du nouveau

modèle à reproduire fidèlement le comportement thermique du manteau neigeux et son impact sur le sol sous-jacent.

Evaluation de la modélisation numérique de la production de neige de culture Le détail de cette partie peut être consulté en section 4.5. La modélisation de la production de neige de culture améliore nettement la représentation des conditions d'enneigement sur piste (Figure 1.16 et Table 4.8), en termes de densité et de surface spécifique. Les profils stratigraphiques ont également été tracés et comparés aux observations pour les 150 cm de surface du manteau neigeux (Figure 1.17) avec une bonne cohérence. L'incertitude majeure associée à la production de neige et sa modélisation repose sur le taux de conversion de l'eau en neige de culture (Section 4.5.3).

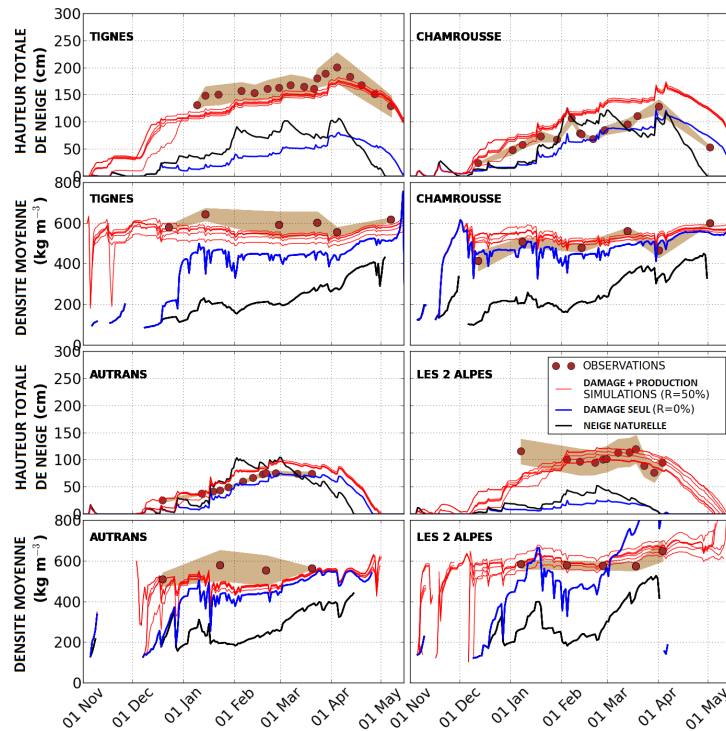


FIGURE 1.16 – Impact du damage et de la production de neige observé sur les propriétés du manteau neigeux (densité moyenne, hauteur de neige). Les simulations par les sept configurations du modèle sont présentées (ratio de perte en eau $R = 50\%$, Table 4.3 et 4.4) ainsi que les simulations par le damage seul (pas de production) et les conditions d'enneigement naturel.

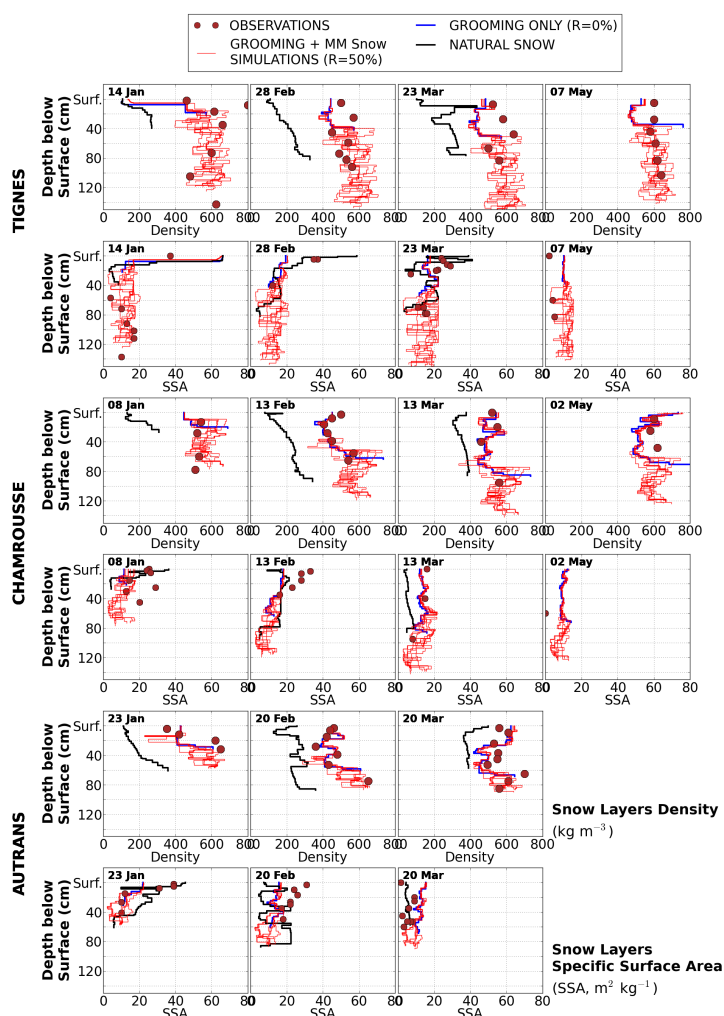


FIGURE 1.17 – Impact du damage et de la production de neige observé sur les propriétés des 150 cm de surface du manteau neigeux (densité, microstructure). Les simulations par les sept configurations du modèle sont présentées (ratio de perte en eau $R = 50\%$, Table 4.3 et 4.4) ainsi que les simulations par le damage seul (pas de production) et les conditions d'enneigement naturel.

Les taux de conversion fournissant les plus faibles écarts entre simulations et observations étaient de 50% à 75% à Tignes, 50% à 25% aux 2 Alpes, 25% à 50% à Chamrousse et Autrans (Figure 1.18 et Table 4.8), des écarts nettement au-delà des observations reportées jusque là (Eisel et al., 1988, 1990; Hanzer et al., 2014; Olefs et al., 2010). Néanmoins, les incertitudes liées aux observations (faible densité spatiale des observations) ne permettaient pas sur la seule saison 2014 - 2015 de conclure sur les facteurs influençant la conversion de l'eau en neige de culture, bien que la topographie et le vent constituent des sources de pertes très probables. Ce constat nous a mené à réaliser une campagne d'observations dédiée à la production de neige de culture et à ce taux de conversion eau/neige.

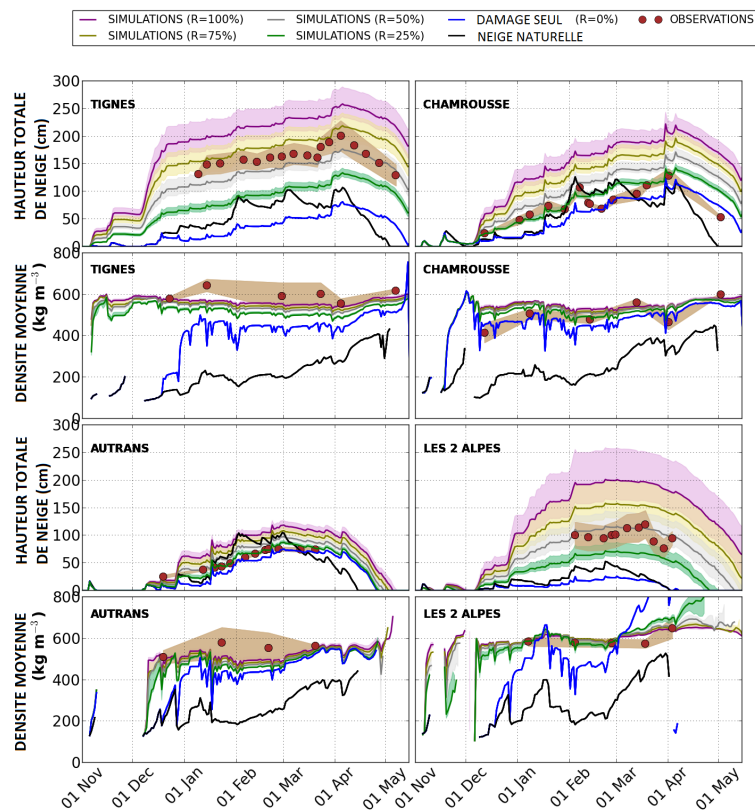


FIGURE 1.18 – Conditions d'enneigement simulées avec prise en compte du damage et de la production de neige (ratios de $R = 100\%$ à 25%). Toutes les simulations utilisent la configuration standard du modèle. Les enveloppes de couleur correspondent aux incertitudes liées principalement à la surface d'étalement de la neige de culture. Les simulations des conditions d'enneigement sans production (damage uniquement) et d'enneigement naturel sont également présentées.

1.4.3 Evaluation du taux de conversion eau - neige de culture (Chapitre 5)

Les pertes en eau au cours du processus de production de neige de culture ont été abordées dans plusieurs études aux approches très différentes (modélisation, entretiens, observations) et visant différents facteurs d'influence (processus thermodynamiques, transport par le vent, etc.). Eisel et al. (1988) ont estimé les pertes nettes au cours de la production associées à l'évaporation et à la sublimation par une combinaison d'observations dans neuf sites expérimentaux (bilans de masse) et de modélisation (bilans d'énergie) et conclu à des pertes de 6% du volume d'eau en moyenne, avec une relation linéaire négative entre les pertes (%) et la température de l'air. Hanzer et al. (2014) ont implémenté cette relation linéaire dans un modèle physique de neige et conclu que pour des conditions de production typiques, les pertes associées aux processus thermodynamiques s'établissaient entre 2 et 13% du volume d'eau employé. Bien que les travaux Eisel et al. (1988, 1990) demeurent les plus détaillés à ce jour, ils n'ont pas été réalisés dans des conditions opérationnelles (faibles débit, maximum 4 m³ d'eau utilisés par session d'observation) et avec une technologie aujourd'hui dépassée. De plus, Eisel et al. (1990) ont montré par la suite que les pertes en eau au cours de la production ne pouvaient être limités aux processus thermodynamiques en établissant le bilan hydrique de six sites expérimentaux dans le Colorado et concluant que des pertes additionnelles de 7 à 33% étaient constatées, portant les pertes totales à 13 à 37% du volume initial pour la production. Ces études comme les résultats présentés dans

la section précédente ne permettaient pas cependant d'établir de bilan précis du fait des incertitudes associées.

Dans ce chapitre, nous proposons une méthode originale d'observation des volumes de neige produits sur une échelle spatiale fine (grille de 0.5 x 0.5 m). Les équivalents en eau (kg m^{-2}) ont été calculés grâce à des mesures de la densité de la neige de culture et la masse totale de neige de culture produite et présente sur la piste a été déduite, permettant la comparaison avec la masse d'eau employée pour la production et le calcul du taux de conversion eau - neige de culture. Ces observations ont été réalisées au cours de l'hiver 2015 - 2016 dans la station des Deux Alpes (Oisans). Les nivoculteurs du domaine nous ont transmis toutes les données de production associées (débit d'eau, température humide observée, vent). Cette méthode est décrite en détails dans la section 5.2.

Zones d'étude et méthodologie Deux types de mesures ont été réalisées sur le site de la piste des Coolidge de la station des Deux Alpes à 1680 m d'altitude de pente faible à cet endroit.

- Après la production de neige et avant le travail des engins de damage, nous avons relevé les volumes des tas de neige de culture produits et leur masse. Cinq sessions de ce type ont été réalisées au cours du même hiver.
- Des relevés de la piste ouverte aux skieurs ont également été réalisés à trois reprises au cours de la saison. Les volumes de neige et leur masse ont été calculés et la masse de neige naturelle présente à chaque date a été soustraite pour déterminer l'apport de neige de culture.

Ces observations reposent sur une méthode de relevés par GPS différentiel de la surface de la neige, interpolés sur une grille régulière (identique au MNT¹⁷ de la station réalisé en octobre 2015) qui permet d'établir la hauteur de neige par différence entre deux surfaces de neige (dans le cas de sessions de production consécutives) ou avec le terrain nu (dans le cas de la piste ouverte aux skieurs). Les incertitudes associées à cette méthode ont été évaluées à l'aide de trois méthodes différentes : le MNT du terrain nu (données relevées le 17 novembre 2015 avec le GPS), un Laser Scan Terrestre le 1^{er} décembre 2015 (session commune avec le GPS) et des mesures manuelles de hauteur de neige avec une perche à neige (en tout 29 mesures). L'erreur sur la hauteur totale de neige a été évaluée à 4.2 cm. Parallèlement, les relevés de densité de neige ont fourni des erreurs sur la densité de l'ordre de 4 à 7%, ce qui constitue une incertitude finale sur la masse de neige par unité de surface de 20 à 35 kg m^{-2} (Section 5.2.3). Une fois intégrée sur la surface totale d'étude, cette masse surfacique a fourni une masse de neige que nous avons pu comparer aux volumes d'eau employés soit par session, soit jusqu'à la date d'observation pour les relevés sur piste ouverte aux skieurs. L'évolution saisonnière de la piste a également pu être comparée aux simulations réalisées avec les données de production jour par jour fournies par les nivoculteurs des Deux Alpes.

Observations des tas de neige de culture (section 5.3.1) La moitié de la production a été concentrée dans une période de temps très courte dans les dix derniers jours de novembre 2015 au cours desquels nous avons pu relever près de 75% de la production. Les conditions étaient idéales avec des températures froides (moyenne de production -9.5°C) et un vent quasi nul. Par la suite un seul relevé a pu être réalisé le 21 janvier 2016 avec des conditions similaires mais un réglage différent du paramètre qualité de l'enneigeur. Sur l'ensemble de la saison, cet enneigeur a utilisé un volume de 2947 m^3 d'eau. La distribution de la neige autour de l'enneigeur a été très similaire entre les sessions (Figures 18a et 18b). Nous avons déterminé le volume puis la masse de neige dans des cercles concentriques autour

17. Modèle Numérique de Terrain : une information sur la position spatiale x,y et d'altitude z du terrain sans neige, à une résolution spatiale donnée, 0.25m^2 dans cette étude.

d'un point fixe correspondant au sommet du tas et comparé cette masse à la masse d'eau employée pour la session de production relevée.

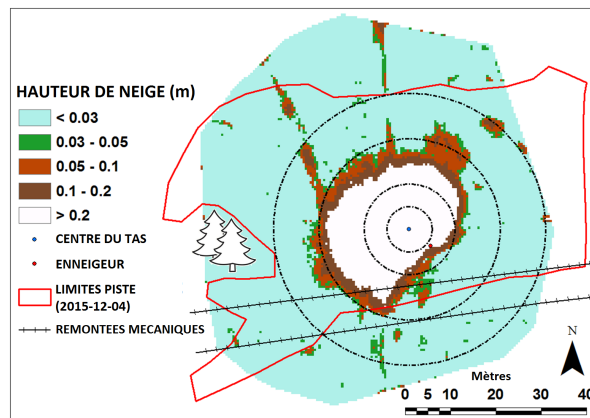


FIGURE 18a – Carte de hauteur totale de neige, position de l'enneigreur, du centre du tas et cercles concentriques de 5, 10, 20 et 30 m de rayon autour du centre du tas. La limite de la piste au 4 décembre 2015 est également présentée.

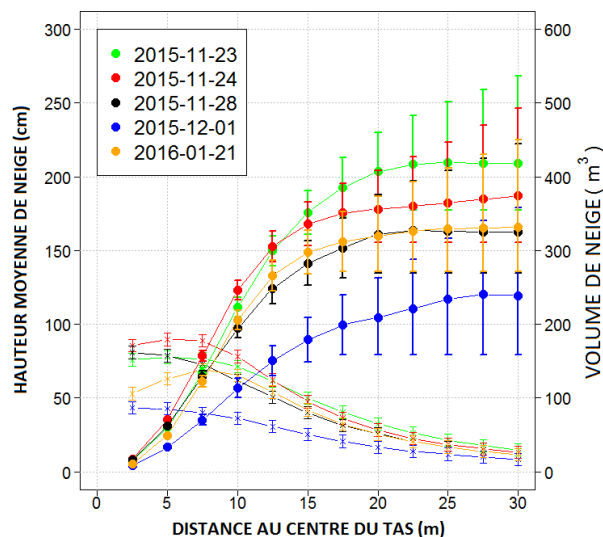


FIGURE 18b – Epaisseur moyenne de neige (x) et volume de neige (●) à l'intérieur des cercles concentriques de 5, 10, 20 et 30 m de rayon autour du centre du tas.

Un taux de conversion très similaire a été observé pour les différentes sessions de novembre avec 20 à 30% de la masse d'eau retrouvée sous forme de neige dans un rayon de 10 m autour du centre du tas et 40 à 50% dans un rayon de 20 m (Figure 1.19). En janvier, ces taux étaient significativement plus élevés, ce qui pose la question de l'influence du paramètre qualité mais également de la représentativité de cette unique mesure dans cette configuration.

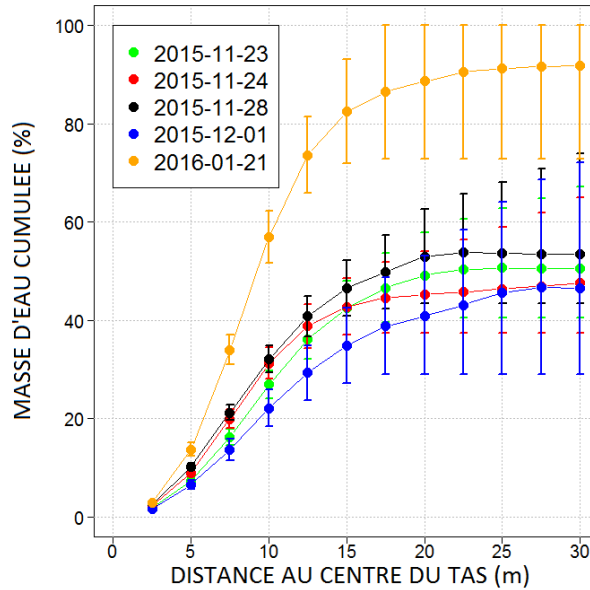


FIGURE 1.19 – Masse d'eau cumulée à l'intérieur des cercles concentriques de 5, 10, 20 et 30 m de rayon autour du centre du tas par rapport à la masse d'eau utilisée pour chaque session de production.

Observations de la piste ouverte aux skieurs (section 5.3.2) La production de neige de culture a considérablement amélioré les conditions de ski sur ce tronçon de piste avec des conditions acceptables (un minimum de 20 cm de neige à 400 kg m^{-3}) pendant 159 jours (observés) alors que cette durée était de 82 jours en neige naturelle damée et de 48 jours en neige naturelle (section 5.3.2). De plus la production de neige a permis le ski au cours des vacances de Noël 2015 alors que la zone des Coolidge était déneigée à cette date (neige naturelle ou damée).

Le 4 décembre 2015 veille d'ouverture, le 20 janvier 2016 et le 6 avril 2016 nous avons réalisé un relevé de l'ensemble du tronçon de piste, ce qui a permis de constater que la variabilité de l'épaisseur de neige était très importante, de l'ordre de 3 à 4 fois supérieure à l'incertitude sur la hauteur de neige. La forme des tas de neige de culture était encore très présente (Figure 1.20) et la distribution initiale de la neige pour l'ouverture de la piste le 5 décembre était encore nettement visible en janvier et en avril.

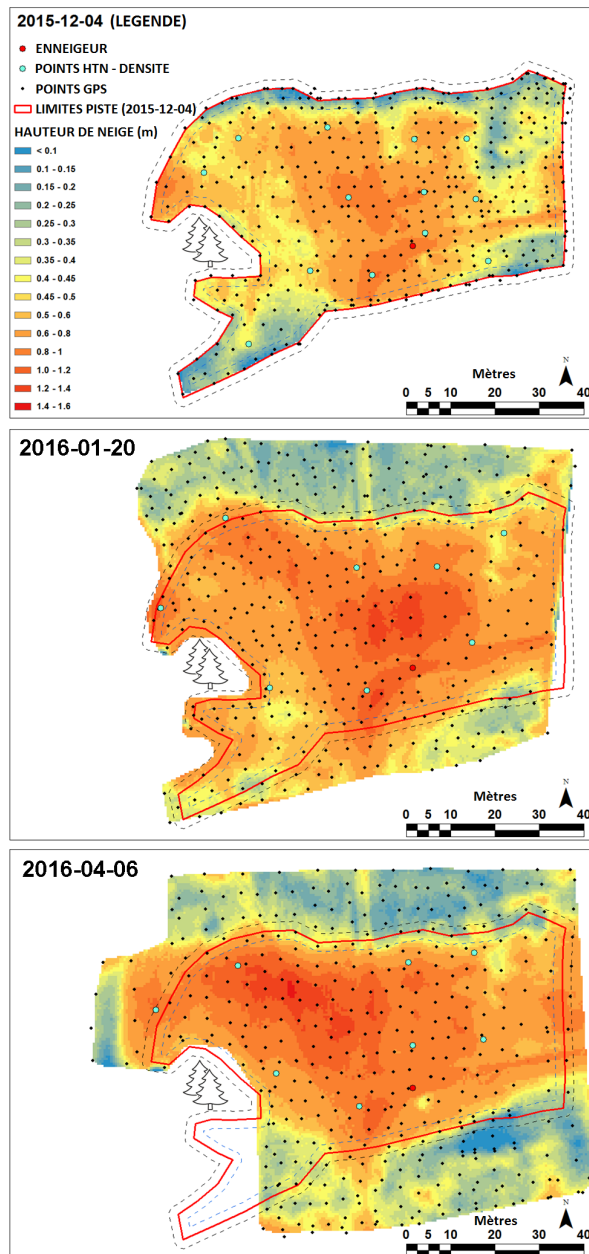


FIGURE 1.20 – Carte des hauteurs de neige observées le 2015-12-04 (haut), 2016-01-20 (milieu) et 2016-04-06 (bas).

A chaque reprise le volume total et la masse de neige correspondante ont été calculés, la masse de neige naturelle de la zone considérée a été soustraite et la différence a été comparée à la masse d'eau employée jusqu'à la date du relevé. Le 4 décembre, cette différence représentait 59.8% ($\pm 10.2\%$) de la masse d'eau employée pour la production jusqu'à date, le 20 janvier 67.9% ($\pm 13.4\%$) et le 6 avril 64.3% ($\pm 10.7\%$), ce qui suggère qu'une part significative du volume d'eau initial utilisé pour la production ne se trouvait pas dans les limites de la piste définie par les services de pistes.

Evolution saisonnière de la piste ouverte aux skieurs et comparaison aux simulations (section 5.3.3) La hauteur de neige et l'équivalent en eau (kg m^{-2}) ont pu être agrégés pour chaque relevé des

conditions sur piste ouverte aux skieurs, fournissant une hauteur et un équivalent eau moyen avec une incertitude associée. Ces informations ont pu être comparées aux simulations réalisées avec le modèle Crocus dont la production quotidienne correspond à l'enregistrement transmis par les nivoculteurs de la station. Sur la période de production initiale (avant le 5 décembre), nous avons réalisé des simulations avec des taux de conversion eau - neige de culture de 100 à 30% avec un pas de 5%. Trois simulations utilisant les taux de 65, 60 et 55% ont fourni des conditions d'enneigement dans l'intervalle d'incertitude des observations. Ces trois situations possibles à la date du 5 décembre ont été ensuite employées comme états initiaux pour de nouvelles simulations sur la période du 5 décembre jusqu'à la fin de la saison avec plusieurs taux de conversion (100%, 65%, 55 et 45%). Trois couples de simulations ont fourni des conditions d'enneigement dans les intervalles d'incertitudes pour les trois dates d'observations : 60% (première période) et 45% (seconde période), ainsi que 55% et 55%, 55% et 45% (Table 5.10). Ces résultats sont cohérents avec ceux déterminés par la méthode précédente et suggèrent que le taux de conversion est similaire entre la période avant le 5 décembre et après. Les durées simulées par ces trois couples de taux de conversion de la saison avec des conditions convenables pour le ski est également cohérente avec les observations avec 164 à 166 jours d'enneigement minimum de 20 cm à 400 kg m^{-3} .

Conclusion sur le taux de conversion et détermination des effets thermodynamiques et mécaniques

Les relevés réalisés sur piste ouverte aux skieurs suggèrent qu'une fraction de l'eau utilisée pour la production n'a pas été retrouvée sous forme de neige à l'intérieur des contours de la piste, de l'ordre de 40% ($\pm 10\%$) en masse. Deux raisons peuvent être à l'origine de ces écarts : les processus thermodynamiques (évaporation et sublimation) et mécaniques (suspension et transport par le vent). Eisel et al. (1988) ont déterminé une relation linéaire entre les pertes en eau associées à l'évaporation et à la sublimation au cours du processus de production (pertes nécessaires au process) que nous avons pu utiliser pour estimer la fraction perdue par ce biais. Sur l'ensemble de la période de production, 6.7% de pertes thermodynamiques ont été estimées (section 5.4). Ce qui est loin d'expliquer les écarts constatés. Par conséquent, une fraction significative du volume d'eau initial n'est pas perdue par évaporation ni sublimation et aboutit certainement à la formation de neige qui n'a cependant pas été mesurée dans les limites de la piste. Pourtant le site expérimental choisi pour cette étude est de grande dimension (largeur de piste minimale 45 m, jusqu'à 75m), bien au-delà de la moyenne française (autour de 20 m). Les conditions de production peuvent également être considérées comme idéales (sans vent, températures froides).

La situation décrite dans le présent travail semble constituer une situation idéale avec une perte significative du volume d'eau initial sans doute de l'ordre de 40% et au minimum de 30%. Cette étude démontre particulièrement que la topographie locale peut jouer un grand rôle dans le taux de conversion eau - neige de culture sur la piste avec seulement 20 à 30%, maximum 50% du volume d'eau retrouvé sous forme de neige dans un rayon de 10 m autour du centre du tas, ce qui correspond (en diamètre) à la largeur moyenne d'une piste de ski en France (Spandre et al., 2016a). Des volumes de neige de culture ont également été observés au pied, voire à l'arrière de l'enneigeur (Figure 18a) ce qui confirme l'idée que la position idéale d'un enneigeur devrait être, si possible, au milieu de la piste. L'environnement immédiat de la piste peut également avoir un rôle important soit en permettant aux engins de circuler et ainsi récupérer ces volumes de neige pour les replacer au centre de la piste, soit les rendre définitivement inaccessibles dans le cas d'obstacles importants (blocs, falaises, arbres). Ce travail est néanmoins soumis à un certain nombre de limitations et ne peut être généralisé qu'avec prudence. Les écarts entre le relevé du 21 janvier par rapport aux autres sessions de production (Figure 1.19) restent largement inexpliqués et plaident pour des observations complémentaires, notamment de l'impact du paramètre "qualité" à

disposition des nivoculteurs pour varier le ratio eau/air des enneigeurs. Toutefois les tendances observées dans le présent travail sont cohérentes avec les précédents travaux sur ces questions (Eisel et al., 1990; Olefs et al., 2010) et suggèrent que la neige de culture, comme tout procédé industriel, dispose d'un rendement optimum qui est significativement en deçà des 100% avec des leviers puissants de pertes additionnelles associées aux caractéristiques du terrain (topographie, vent local) et au mode d'utilisation (paramètre "qualité"). Il convient par conséquent de redoubler de prudence à l'installation comme à l'utilisation de la neige de culture qui s'avère être un appui non négligeable dont l'intérêt et l'usage doivent cependant être questionnés à chaque étape. Les conditions marginales de production semblent être des facteurs de pertes très puissants que nous suggérons de ne pas négliger. La qualité de production la plus élevée possible doit être privilégiée et la production par vent non nul (supérieur à quelques km h⁻¹) doit être, dans la mesure du possible, évitée. Le gaspillage de la neige de culture doit faire l'objet de la plus grande attention par les nivoculteurs, tout comme la surproduction, sans quoi son intérêt pourrait être largement remis en question.

1.5 Détermination et application d'indicateurs de la viabilité de l'enneigement dans les domaines skiables des Alpes françaises sur la période 1958 - 2014 (Chapitre 6)

1.5.1 Introduction et méthodes

Introduction Cette section décrit l'intégration du modèle physique de simulations des conditions d'enneigement incluant l'influence du damage et de la production de neige avec les représentations spatiales des domaines skiables dites "enveloppes gravitaires" développées par Francois et al. (2016) pour l'ensemble des stations des Alpes françaises. La répartition des équipements en enneigeurs à l'intérieur du domaine skiable a également été simulée. Les conditions d'enneigement ont été simulées pour la période 1958 - 2014¹⁸ en prenant en compte l'enneigement naturel uniquement, l'effet du damage et le damage associé à trois niveaux d'équipement en neige de culture (15, 30 et 45% de surfaces équipées en enneigeurs). Nous avons défini des indices de la viabilité de l'enneigement dont nous avons déterminé la corrélation avec le nombre de journées skieurs sur la période 2001 - 2014 (DSF, 2014) et comparé les résultats avec des études existantes (Abegg et al., 2007; François et al., 2014). Les volumes d'eau nécessaires pour la production de neige et la consommation électrique associée ont été calculés pour la période 1985 - 2014 et comparés avec les données disponibles (Badré et al., 2009).

Zone d'étude Les Alpes françaises regroupent l'offre de ski la plus importante à l'échelle nationale avec 141 des 220 stations françaises (64%) situées dans cette région, dont 106 (48%) dans les Alpes du Nord (NA) et 35 (16%) dans les Alpes du Sud (SA). D'après le service d'Observation, Développement et Ingénierie Touristiques (ODIT, 2009), 84% des remontées mécaniques (RM) nationales sont implantées dans les Alpes (69% NA + 15% SA) et 84% des surfaces des pistes de ski (64% NA + 19% SA). Le nombre de journées skieurs vendues par les opérateurs de remontées mécaniques est largement réalisé dans les Alpes (89%, 78% NA + 11% SA) tout comme les emplois générés par l'industrie du ski (DSF, 2014) : 105 000 des 120 000 emplois (88%, 75% NA + 13% SA). Sur la période 2001 - 2014 la France s'est partagée la première place mondiale en nombre de journées skieurs vendues avec les Etats

¹⁸. La période 1958 - 2014 court du 1^{er} Août 1958 au 31 Juillet 2015. NB : la saison "2001" désigne l'hiver 2001 - 2002.

Unis et l'Autriche avec une moyenne de 53.9 millions de forfaits vendus (Abegg et al., 2007; DSF, 2014). Domaines Skiabiles de France (DSF) distingue cinq périodes au cours de la saison d'hiver dont l'importance économique relative est assez stable dans le temps (DSF, 2014). La période d'ouverture jusqu'à la fin des vacances de Noël représente 25 à 30% des ventes annuelles de journées skieurs et les vacances scolaires d'hiver 30 à 35% (DSF, 2014). Une répartition similaire des nuitées a été publiée par Savoie Mont-Blanc tourisme¹⁹ avec 19% des nuitées vendues au cours des vacances de Noël et 33% au cours des vacances scolaires d'hiver (Lecuret et al., 2014). Le nombre de journées skieurs vendues nous a été fourni par Domaines Skiabiles de France pour la période 1990 - 2014, révélant une augmentation statistiquement significative (Onwuegbuzie et al., 2007) sur la période 1990 - 2001 ($R^2 = 0.69$, p -value = 8.10^{-4}) avec une augmentation moyenne de 600 000 journées skieurs supplémentaires par an. A partir de 2001, l'évolution tendancielle des journées skieurs vendues n'est plus statistiquement significative ($R^2 = 0.16$, p -value = 0.15). Nous avons donc considéré dans cette étude les périodes suivantes : la période la plus longue pour laquelle nous disposons de données météorologiques (1958 - 2014), la période depuis le début des installations en enneigeurs (1985 - 2014) et la période depuis la stagnation des ventes de journées skieurs (2001 - 2014).

Modélisation de la neige Le modèle SAFRAN/SURFEX/ISBA-Crocus (Brun et al., 1992; Vionnet et al., 2012) a été utilisé pour cette étude, avec les récents développements baptisés "Crocus-Resort" permettant la prise en compte de la production de neige et du damage (Spandre et al., 2016c). Le schéma de production de neige a été déterminé d'après la française (Hennessy et al., 2007; Steiger, 2010; Hanzer et al., 2014) et en particulier en s'appuyant sur l'étude que nous avons réalisée sur les pratiques professionnelles (Spandre et al., 2016a). La saison hivernale a été divisée en trois temps :

- Entre le 1^{er} novembre et le 15 décembre, une sous couche de 30 cm de neige de culture (150 kg m^{-2}) est produite, si les conditions météorologiques le permettent, quel que soit l'enneigement au cours de cette période ;
- Entre le 15 décembre et le 28 février, de la neige est produite, si les conditions météorologiques le permettent, pour maintenir une épaisseur totale de neige sur la piste de 60 cm ;
- Après le 1^{er} mars la production n'est plus possible.

En France, nous avons déterminé une moyenne de 2.5 à 3.1 enneigeurs de type perche par hectare de piste (Spandre et al., 2016a). Nous avons donc considéré que chaque enneigeur produit de la neige sur une surface moyenne de 3500 m^2 , avec un débit d'eau moyen de $15 \text{ m}^3 \text{ h}^{-1}$, ce qui fournit un taux de production de neige de culture de $1.2 \cdot 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$. Dans le modèle Crocus-Resort, la production est possible de 18h à 8h le lendemain matin (Spandre et al., 2016c), ce qui permet une production maximale de 60 kg m^{-2} de neige sur les surfaces équipées, ce qui équivaut à une épaisseur de 12 cm de neige de culture. Le critère de déclenchement de la production a été fixé au seuil de limite technique de -2°C (température dite "humide" ou température du thermomètre mouillé). Une vitesse de vent de 4.2 m s^{-1} maximum est permise pour la production de neige (Spandre et al., 2016c).

Données structurelles sur les domaines skiables La base de données "BD stations" a été employée dans cette étude pour fournir les données structurelles sur les domaines skiables (remontées mécaniques, altitudes, zones urbaines, etc.). Les représentations spatiales des domaines skiables développées par Francois et al. (2016), dites des "enveloppes gravitaires", ont été utilisées dans cette étude. Pour des raisons techniques, ces enveloppes gravitaires n'ont pu être exploitées que pour 129 stations des Alpes dont le total des infrastructures correspond à 96% des infrastructures alpines.

19. Départements de Savoie (73) et Haute-Savoie (74)

Nous avons également utilisé les altitudes ci-dessous :

- L'altitude moyenne des RM d'une station est définie comme l'altitude moyenne de chaque RM pondérée par son moment de puissance. Cette altitude est corrélée ($R^2 = 0.93$) à l'altitude médiane du domaine skiable (altitude moyenne entre le point le plus haut et le point le plus bas du domaine). L'écart moyen est - 8 m (écart type 91 m).
- L'altitude moyenne du bâti immobilier de la station, baptisée "altitude du village" et définie comme l'altitude moyenne de chaque zone urbaine pondérée par sa surface (Breiling and Charanza, 1999).

Ces altitudes étaient, elles, disponibles pour l'ensemble des 129 stations alpines traitées dans ce travail. Les domaines dont la gestion est assurée par une même société sont agrégées dans cette étude (François et al., 2014). Par exemple, la vallée de Chamonix est gérée par la Compagnie du Mont-Blanc (Le Tour, Brévents/Flégère, les Bossons, Montenvers, Aiguille du Midi et Les Grands Montets) ou les stations du Mercantour gérées par l'opérateur Cimes du Mercantour (Auron, Isola 2000, La Colmiane).

Distribution spatiale des enneigeurs au sein des domaines La répartition spatiale des enneigeurs au sein des domaines skiables a été simulée selon une méthode similaire à celle des "enveloppes gravitaires" et sur la littérature disponible sur les équipements en enneigeurs dans les Alpes françaises (Agrawala et al., 2007; Spandre et al., 2015, 2016a). Au cours de ce travail de thèse, nous avons déduit de nos travaux que l'objectif des enneigeurs était de garantir une zone skiable, en priorité sur les pistes les plus accessibles aux skieurs de tous niveaux et qui permettent une continuité du ski entre le haut de RM sélectionnées jusqu'au village (Spandre et al., 2016a). Abegg et al. (2007) ont également indiqué que 15% des pistes étaient équipées en enneigeurs en France en 2003 et nous avons estimé que près de 32% des pistes étaient équipées en 2015 (Spandre et al., 2015) et pourraient atteindre 43% en 2020. Nous avons donc construit des représentations spatiales des zones équipées en enneigeurs au sein des domaines skiables pour trois taux d'équipement (15%, 30% et 45%) et en suivant les règles suivantes (Figure 1.22) :

- **Etape 1** : les RM les plus proches du village sont sélectionnées à partir de trois critères.
 - La distance au bâti. Marcelpoil et al. (2012) ont défini les bâtiments appartenants à un domaine skiable comme étant situés à une distance de 300 m maximum du bas d'une RM. A partir de ces bâtis, Fablet (2013) a défini des zones urbaines autour de ces bâtiments dont le nombre varie pour chaque zone urbaine (Figure 1.22). Les bâtiments isolés ont été exclus. Nous avons ensuite défini et sélectionné les RM prioritaires comme étant distantes de 300 m maximum des zones urbaines de la station.
 - L'altitude du bâti. Les zones urbaines dont l'altitude excède de plus de 30% l'altitude moyenne du village sont exclues. Nous avons supposé que ces bâtiments correspondaient en majorité à des bâtiments techniques (gares de RM) et/ou à des restaurants d'altitude.
 - La taille des zones urbaines. Les zones urbaines constituées de moins de cinq bâtiments ont été exclues et les RM à moins de 300 m des ces zones n'ont pas été sélectionnées (Figure 1.22).
- **Etape 2** : L'ensemble des points accessibles par gravité depuis le haut et permettant de rejoindre le bas des RM de la sélection de l'étape 1 sont sélectionnés à leur tour. Les points dont la pente est supérieure à 25° sont exclus. L'ensemble de ces points constitue une enveloppe dite de neige de culture.
- **Etape 3** : La taille de cette enveloppe de neige de culture est comparée à la taille de l'enveloppe gravitaire du domaine skiable. Si le ratio est différent du taux d'équipement souhaité (15, 30 ou 45%), une ultime étape est réalisée :

- Si le ratio est plus faible que souhaité (exemple des Deux Alpes, Figure 1.22), nous avons considéré les pixels formant le contour de l'enveloppe de neige de culture et sélectionné pour chacun l'ensemble de ses voisins dont l'altitude est plus élevée que la sienne. Cette étape a été répétée jusqu'à obtenir le ratio souhaité;
- Si le ratio est plus élevé que souhaité (exemple des Sept Laux, Figure 1.22), tous les pixels à partir de l'altitude la plus élevée de l'enveloppe de neige de culture ont été supprimés jusqu'à ce que le ratio souhaité soit atteint.

Cette méthode permet de produire des représentations spatiales des zones équipées en priorité par les enneigeurs. L'altitude maximum de ces enveloppes de neige de culture a été extraite. Conformément aux résultats de notre enquête, cette altitude était statistiquement corrélée à l'altitude moyenne des RM pour chaque station (Figure 1.21).

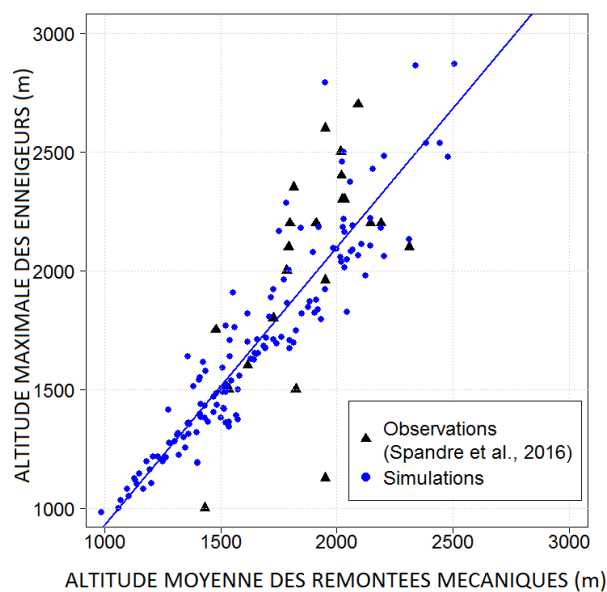


FIGURE 1.21 – Altitude maximum des enveloppes de neige de culture (pour un taux d'équipement de 30%) par rapport à l'altitude moyenne des remontées mécaniques des domaines skiables. En noir les données d'après Spandre et al. (2016a). Le modèle linéaire a une pente de 1.17.

La méthode de couplage des conditions d'enneigement simulées avec les représentations spatiales des domaines skiables est identique aux développements initiaux de François et al. (2014) et peut être consultée en détails dans la section 6.3.4. Lorsque la neige de culture est prise en compte et en fonction du taux d'équipement, une étape supplémentaire est réalisée pour déterminer si un pixel de l'enveloppe gravitaire appartient à l'enveloppe de neige de culture.

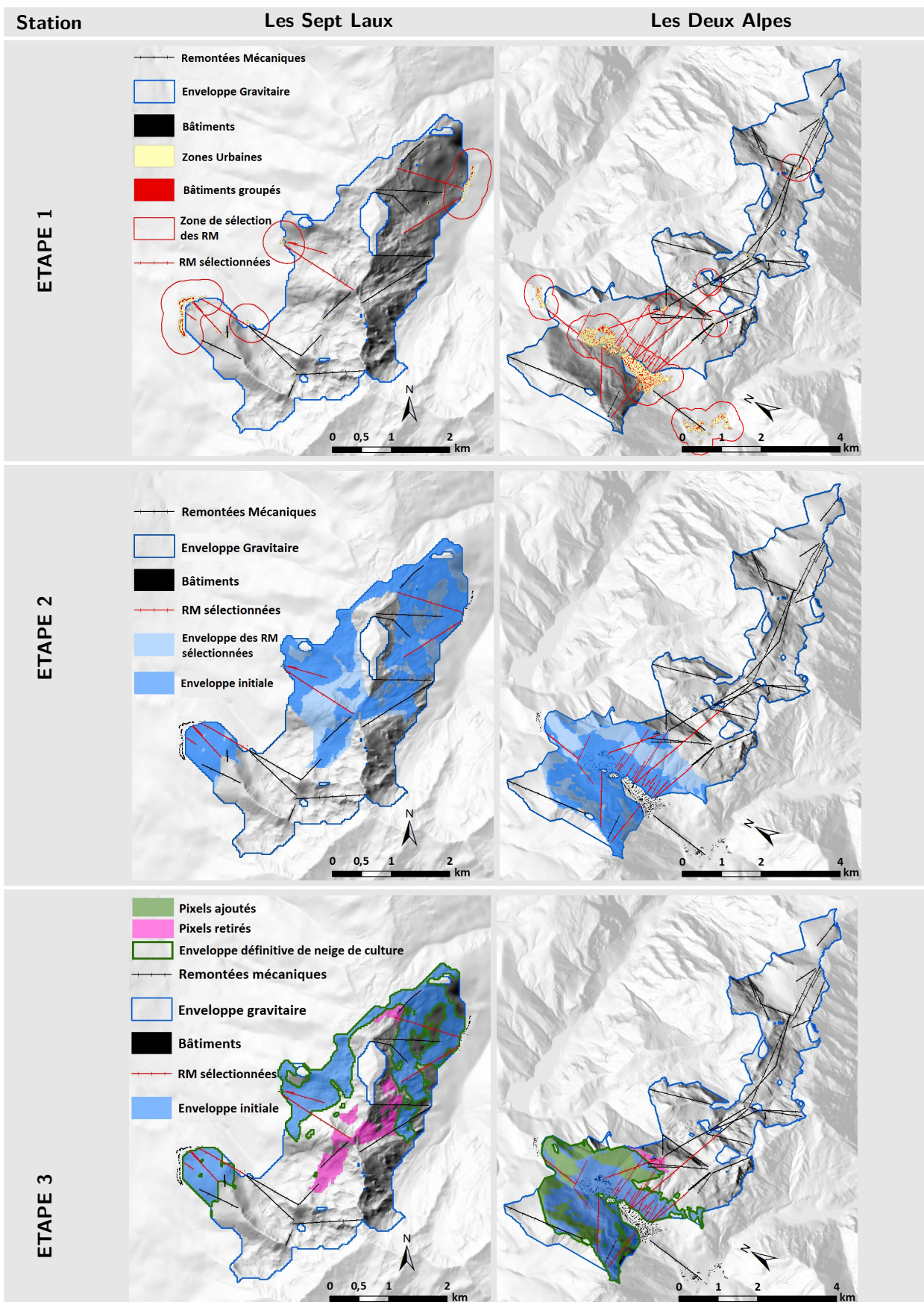


FIGURE 1.22 – Détermination des secteurs prioritaires pour l'implantation de la neige de culture sur les domaines skiables Les Sept Laux (Belledonne, France, gauche) et Les Deux Alpes (Oisans, France, droite). Les remontées mécaniques sont sélectionnées dans une distance maximum de 300m autour des bâtiments groupés (minimum 5 bâtiments et altitude limitée, étape 1). Les pentes accessibles depuis ces RM sont sélectionnées avec exclusion des pentes supérieures à 25° (étape 2). Des pixels sont ajoutés ou supprimés à cette enveloppe initiale pour atteindre l'objectif de couverture en équipement de neige de culture (ici 30%) pour fournir l'enveloppe définitive de neige de culture (étape 3).

Indicateurs de la viabilité d'enneigement L'Altitude de Viabilité de l'Enneigement (AVE, Table 1.3) a été déterminée pour les 23 massifs alpins sur la période 1958 - 2014 (Elsasser et al., 2002; Abegg et al., 2007). Cette altitude correspond pour chaque massif à l'altitude à laquelle la quantité de neige dépasse 100 kg m^{-2} (20 cm de neige damée à 500 kg m^{-3}) pendant un moins 100 jours entre le 15 décembre et le 15 avril. Trois altitudes ont été calculées : l'altitude à laquelle ces conditions sont respectées en neige damée en moyenne ("GS Av."), l'altitude à laquelle ces conditions sont respectées en neige damée pour 70% des saisons sur l'ensemble de la période ("GS >70%") et l'altitude à laquelle ces conditions sont respectées avec production de neige pour 90% au moins des saisons sur l'ensemble de la période ("GS+SM >90%"). Les altitudes moyennes des RM et du village de chaque station ont été comparées à cette altitude AVE. Cette approche ne prend donc pas compte les représentations spatiales des domaines skiables et des enveloppes de neige de culture décrites plus haut.

Un second indicateur a été calculé en prenant en compte les représentations spatiales de chaque domaine. Chaque jour la proportion du domaine skiable qui présente une quantité de neige d'au moins 100 kg m^{-2} (20 cm de neige damée à 500 kg m^{-3}) est calculée. Cet indice quotidien de la viabilité du domaine skiable est calculé pour chaque station des Alpes françaises et pour chaque journée entre le 1^{er} novembre et le 15 mai de 1958 à 2014. Cet indice est ensuite calculé pour les périodes des vacances de Noël (20 décembre - 5 janvier) et des vacances scolaires d'hiver (5 février - 5 mars) en prenant la moyenne des indices quotidiens pour chacune des deux périodes. L'indice de viabilité annuel d'une station est défini comme la combinaison de ces deux indices dont les poids relatifs sont 17% pour les vacances de Noël et 83% pour les vacances scolaires d'hiver. Ces poids relatifs ont fourni la meilleure corrélation possible avec les journées skieurs fournies par Domaines Skiables de France. Le détail de ce travail peut être consulté dans les sections 6.3.6 et 6.4.3. L'indice annuel agrégé sur l'ensemble des 121 stations (pondéré par le moment de puissance de chacune) a été baptisé "vacances combinées". Un dernier indicateur a été calculé comme la moyenne saisonnière des indices quotidiens de la viabilité d'un domaine skiable, dont les résultats ne sont pas détaillés ici.

Massif	Altitude de Viabilité de l'Enneigement (AVE, m)			Total (N)	Nombre de stations (n) au dessus de l'AVE					
	GS Av.	GS > 70%	GS+SM > 90%		à l'altitude du Village			à l'altitude moyenne des RM		
					GS Av.	GS > 70%	GS+SM > 90%	GS Av.	GS > 70%	GS+SM > 90%
Chablais	1309	1372	870 (90%)	18	3	3	17	15	14	18
Aravis	1257	1323	750 (96%)	13	1	0	12	8	6	13
Mont-Blanc	1343	1415	1050 (100%)	7	1	0	6	7	6	7
Bauges	1301	1348	814 (90%)	4	1	1	4	4	4	4
Beaufortain	1368	1463	750 (91%)	5	1	0	5	5	4	5
Haute-Tarentaise	1479	1617	750 (93%)	5	4	4	5	5	5	5
Chartreuse	1401	1476	867 (90%)	6	0	0	6	1	0	6
Belledonne	1410	1463	850 (90%)	3	2	1	3	3	3	3
Maurienne	1478	1613	729 (90%)	7	6	2	7	7	7	7
Vanoise	1574	1715	750 (96%)	11	4	3	11	10	11	11
Haute-Maurienne	1942	1988	1050 (98%)	6	0	0	6	3	3	6
Grandes Rousses	1639	1773	750 (91%)	3	2	0	3	3	3	3
Thabor	1895	1958	1350 (95%)	2	0	0	2	1	1	2
Vercors	1537	1611	1125 (90%)	10	0	0	5	1	0	10
Oisans	1705	1841	1100 (90%)	8	0	0	6	3	2	7
Pelvoux	1767	1898	1050 (100%)	3	0	0	3	2	2	3
Queyras	2209	2334	1050 (100%)	1	0	0	1	0	0	1
Devoluy	1859	1904	1385 (90%)	2	0	0	1	0	0	1
Champsaur	1880	1978	1050 (98%)	3	0	0	3	1	1	3
Embrunais-Parpaillon	2183	2334	1020 (90%)	3	0	0	3	1	0	3
Ubaye	2219	2398	1050 (90%)	4	0	0	4	0	0	4
Haut-Var - Haut-Verdon	2137	2165	1433 (90%)	4	0	0	4	0	0	4
Mercantour	2167	2229	1460 (90%)	1	0	0	1	0	0	1
Alpes du Nord	1480	1570	870	106	25	14	96	75	67	105
Alpes du Sud	2035	2130	1170	23	0	0	22	5	4	22

TABLE 1.3 – Altitude de Viabilité de l'Enneigement (AVE) pour les 23 massifs alpins sur la période 1958 - 2014 basées sur un enneigement minimum de 100 kg m^{-2} pendant 100 jours ou plus entre le 15 décembre et le 15 avril. Les Alpes du Sud sont soulignées en gris foncé et les Alpes du Nord en gris clair. Les altitudes calculées correspondent aux altitudes où ces conditions d'enneigement sont respectées en moyenne ("GS Av.") et pour au moins 7 saisons sur 10 ("GS >70%") en conditions de neige damée. "GS+SM >90%" correspond à l'altitude à laquelle ces conditions d'enneigement sont respectées pour au moins 9 saisons sur 10 ("GS >90%") en prenant en compte le damage et la production de neige. Nous avons également (dans ce cas) détaillé la probabilité associée lorsque la plus faible altitude du système SAFRAN présentait une probabilité supérieure à 90% (12 massifs sur 23). Le nombre total de stations par massif (N) ainsi que le nombre de stations situées au dessus de l'altitude de viabilité de l'enneigement (n) en considérant l'altitude du village ("Village") ou l'altitude moyenne des remontées mécaniques ("RM").

Détermination des besoins en eau et en énergie pour la production de neige Cette chaîne de modélisation physique des conditions d'enneigement permet d'enregistrer la quantité quotidienne (kg m^{-2}) de neige produite par le modèle pour chaque point d'une station. A la fin d'une saison, ces quantités peuvent être agrégées à l'échelle de la station pour fournir un volume d'eau employé pour la production, tel que simulé par le modèle. Le cumul des volumes de l'ensemble des stations a fourni un volume d'eau nécessaire pour l'échantillon de 129 stations de cette étude. Ce calcul a été réalisé pour les trois taux de pistes équipées en neige de culture (15, 30 ou 45%). Le taux réel d'équipement à l'échelle nationale entre 1985 et 2014 a été extrait de la littérature (Hahn, 2004; Abegg et al., 2007; Odit, 2009; Spandre et al., 2015). Pour chaque saison le volume correspondant au taux réel d'équipement a été

calculé par une approximation linéaire à partir des volumes obtenus pour 15, 30 et 45% de couverture (voir section 6.3.7). Enfin, Francois et al. (2016) ont calculé le rapport entre la surface réelle de pistes et la surface des enveloppes gravitaires et déterminé une moyenne de 11% dans les Alpes. Le volume d'eau correspondant aux besoins sur les pistes de ski a donc été calculé à partir du volume simulé, du taux réel d'équipement en neige de culture dans les Alpes françaises pour chaque saison entre 1985 et 2014 et du ratio entre le domaine gravitaire et les surfaces de pistes. A l'aide de cette méthode la surface totale de pistes pour les 129 stations de cette étude était de 16 133 hectares. La quantité d'énergie nécessaire à la production a ensuite été calculée à partir des volumes annuels agrégés sur l'ensemble des stations et d'un besoin énergétique moyen de 6 kWh par m³ d'eau (Rixen et al., 2011; Hahn, 2004).

1.5.2 Viabilité aux conditions d'enneigement et besoin en neige de culture

Altitude de Viabilité de l'Enneigement (AVE) L'ensemble des résultats peut être consulté par massif dans la table 1.3 (Section 6.4.2). Six Petites station sur 55 (11%) ont un village situé au dessus de l'AVE moyenne en neige damée "GS Av." et 20 (36%) ont une altitude moyenne des RM plus élevée. Les Très Grandes stations sont 8 sur 14 à être situées au dessus de cette AVE moyenne en neige damée à l'altitude de leur village et 13 ont une altitude moyenne des RM plus élevée (93%). Sur l'ensemble des 129 stations, 25 ont une altitude du village plus élevée que l'AVE moyenne en neige damée (19%). Aucune n'est située dans les Alpes du Sud. A l'altitude moyenne des RM, 80 stations sur 129 sont plus élevées que l'AVE moyenne en neige damée (62%) et 71 sur 129 (55%) sont plus élevées que l'AVE basée sur une probabilité de 70% ("GS>70%"). En prenant en compte la production de neige de culture, douze des 23 massifs avaient une probabilité supérieure ou égale à 90% d'avoir une quantité de neige de 100 kg m⁻² pendant au moins 100 jours à l'altitude la plus faible du système SAFRAN (Table 1.3). A l'altitude moyenne des RM, 127 stations sur 129 (98%) sont plus élevées que l'AVE avec production de neige de culture "GS+SM>90%". A l'altitude du village, 118 stations sur 129 (91%) sont plus élevées que l'AVE avec production de neige de culture "GS+SM>90%".

Corrélation entre l'indice de viabilité de l'enneigement et les journées skieurs (Section 6.4.3)

La corrélation des journées skieurs à l'indice de viabilité "vacances combinées" est excellente pour l'ensemble des simulations réalisées (neige naturelle, damée ou avec production de neige) avec un coefficient de corrélation R² entre 0.85 et 0.91 (Table 6.4). L'amplitude des fluctuations des journées skieurs au cours de la période 2001 - 2014 est la mieux représentée par l'indice de viabilité "vacances combinées" pour un taux d'équipement entre 15 et 30% ce qui est très cohérent avec l'équipement réel au cours de cette période. Cet indice "vacances combinées" montre une variabilité assez importante depuis 1958 (Table 6.5, Figure 1.23) avec une moyenne en neige naturelle de 84.4% sur la décennie 1985 - 1994 et de 93.8% sur la décennie 1975 - 1984. La variabilité spatiale de cet indice est également forte avec un indice moyen plus faible et un écart-type plus élevé pour les massifs des Alpes du Sud et les massifs pré alpins (Table 6.6, Figure 1.24).

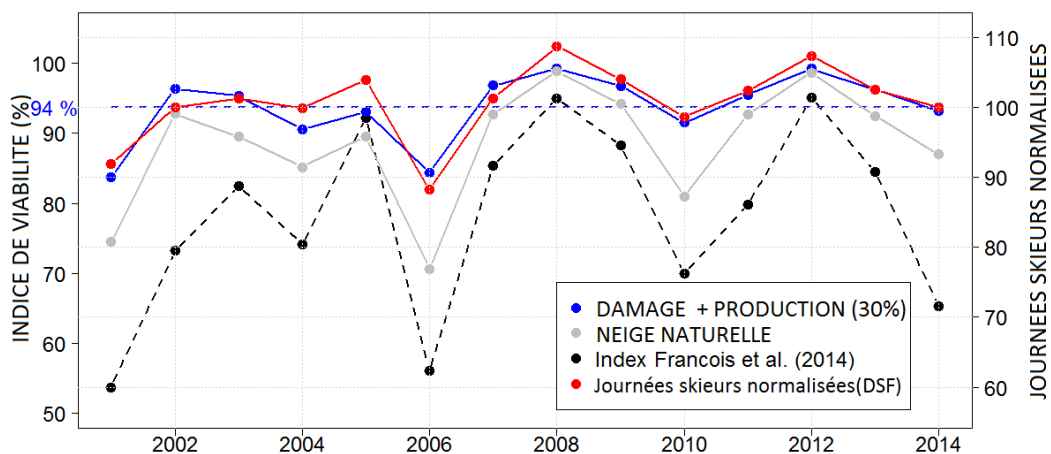


FIGURE 1.23 – L'indice de viabilité des vacances combinées (%) sur la base de l'enneigement naturel et en prenant en compte la gestion de la neige (30% d'équipement en neige de culture), sur la période 2001 - 2014. Les journées skieurs normalisées (évolution relative à la moyenne sur la période) et agrégées au niveau national (données DSF) et l'indice de viabilité de François et al. (2014) sont également présentés. Les axes y ont une même échelle avec le 100% des journées skieurs normalisées (moyenne) centré sur la moyenne de l'indice de viabilité sur la période 2001 - 2014 (94%).

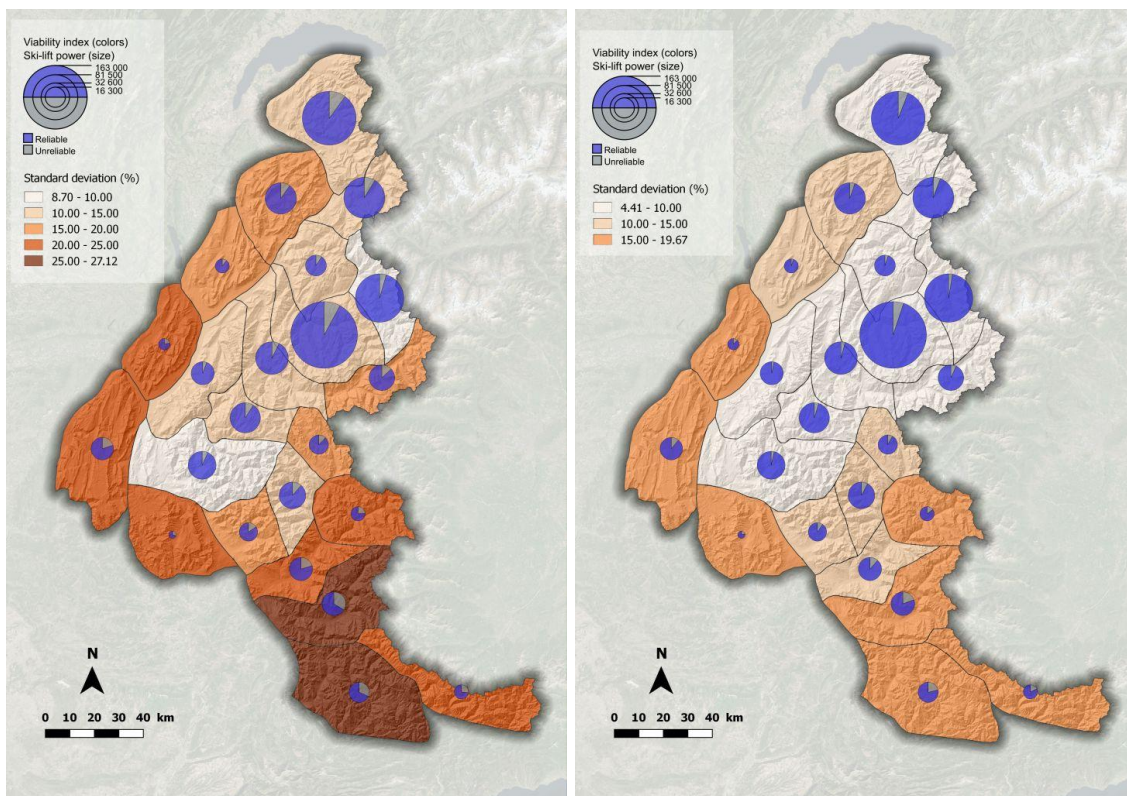


FIGURE 1.24 – Viabilité de l’enneigement des 23 massifs alpins au cours de la période 1958 - 2014 (indice de vacances combinées) en conditions d’enneigement naturel (gauche) et en prenant en compte l’impact du damage et de la production de neige de culture (30% d’équipement, droite). Pour chaque massif le camembert correspond à l’indice de viabilité moyen and la couleur de fond (tons bruns) correspond à la variabilité (écart-type) de l’indice de viabilité sur la période 1958 - 2014. La taille du camembert est proportionnelle aux infrastructures présentes dans le massif considéré.

L’indice “vacances combinées” montre également une forte sensibilité à la taille de la station : plus la station est grande, plus l’indice moyen est bon et moins sa variabilité (écart-type) est importante (Table 6.7). Sur l’ensemble de la période 1958 - 2014 cet indice “vacances combinées” (en neige naturelle, damée ou avec production de neige) n’a pas connu d’évolution statistiquement significative à l’échelle des 129 stations.

Besoins en eau et en énergie Sur l’ensemble des 129 stations traitées, le besoin en neige de culture entre 1985 et 2014 était en moyenne de 1982 m^3 d’eau par hectare (ha^{-1}) de piste avec un écart type de $390 \text{ m}^3 \text{ ha}^{-1}$, un minimum de $1509 \text{ m}^3 \text{ ha}^{-1}$ et un maximum de $3072 \text{ m}^3 \text{ ha}^{-1}$. Ces consommations correspondent à une épaisseur moyenne de neige de culture de 39.6 cm avec un minimum de 30.1 cm et un maximum de 61.4 cm. Ces valeurs sont similaires à celles observées par Rixen et al. (2011) à partir de données de deux stations en Suisse. Le besoin simulé en eau par hectare permettant d’atteindre les objectifs d’enneigement n’a pas montré d’évolution statistiquement significative sur la période 1985 - 2014. La croissance continue et soutenue du besoin total est liée à la croissance significative du taux d’équipement en enneigeurs, de moins de 1% des pistes équipées en 1985 à 32% en 2015 (Figure 1.25). La consommation totale d’énergie pour la production de neige de culture a été estimée à partir des

volumes simulés et à une consommation de 6 kWh par m³ d'eau ($\pm 1 \text{ kWh m}^{-3}$). La consommation énergétique totale a été estimée à 25.5 GWh ($\pm 13.5 \text{ GWh}$) en 2003 quand le ratio de pistes équipées en enneigeurs était de 15% (Hahn, 2004) et à 61.0 GWh ($\pm 32.3 \text{ GWh}$) en 2013 quand ce ratio a atteint 30% (Spandre et al., 2015).

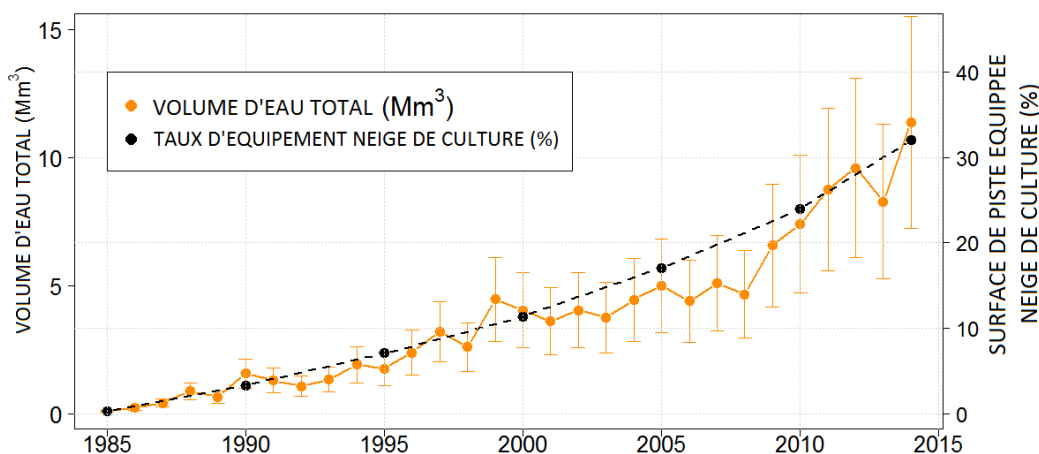


FIGURE 1.25 – Volumes d'eau simulés pour la production de neige de culture (Mm³ ou millions de m³) est le produit du volume d'eau par hectare par la surface de piste équipée en neige de culture. L'incertitude est liée à la conversion entre la surface des domaines gravitaires et la surface effective des pistes de ski d'un domaine skiable. L'évolution du taux d'équipement en neige de culture depuis 30 ans est clairement le principal moteur de l'évolution du besoin en eau pour la production de neige de culture.

Elements de discussion Plusieurs éléments de méthode ou dans les résultats de cette étude font l'objet d'une discussion dans la section ???. Je ne développerai qu'un seul de ces éléments qui concerne les besoins en neige de culture que nous avons calculés ici. D'après des études de ODIT (2009) et Badré et al. (2009) sur la base d'indications fournies par les domaines skiables le volume d'eau total employé pour la production de neige de culture en France était de 6 Mm³ (millions de m³) en 2003 quand 7% des pistes étaient équipées en enneigeurs et de 18.9 Mm³ en 2007 quand 20% des pistes étaient équipées. Dans la mesure où les 129 stations de cette étude représentent 96% des infrastructures de RM alpines et 80.6% des infrastructures de RM nationales et que les RM sont significativement corrélées aux surfaces de pistes, nous avons estimé que le volume de ODIT (2009) et Badré et al. (2009) correspondant aux 129 stations de notre étude était 4.8 Mm³ en 1995 et 15.2 Mm³ en 2007. Les besoins simulés par notre approche étaient de 2.6 Mm³ (contre 4.8 Mm³) en 1995 et 5.7 Mm³ (contre 15.2 Mm³) en 2007 soit un facteur de 1.8 à 2.7. Badré et al. (2009) ont estimé que le besoin en eau par hectare de piste était assez stable entre 1995 et 2007 avec une moyenne de 3500 m³ ha⁻¹. Notre méthode sous estime donc nettement les besoins en eau, ce que nous tentons d'expliquer par trois raisons. D'abord, il est tout à fait possible que les domaines skiables produisent plus de neige que nous ne l'avons simulé, bien que notre approche de la production de neige soit cohérente avec les différentes études sur ces questions (Scott and McBoyle, 2007; Steiger, 2010; Hanzer et al., 2014; Spandre et al., 2016a). Ensuite, nous n'avons pas tenu compte des pertes en eau au cours du processus de production de la neige alors que plusieurs études (dont cette thèse) ont montré que ces pertes peuvent être importantes (Eisel et al., 1988,

1990; Olefs et al., 2010; Spandre et al., 2016b). Enfin, la surface totale de piste, et donc les surfaces de pistes équipées en enneigeurs, simulées par cette étude sont nettement inférieures aux chiffres de ODIT (2009). Si les 129 stations représentent 96% des pistes des Alpes françaises, la surface de piste correspondante à cet échantillon est de 21 393 ha d'après ODIT (2009) contre les 16 133 ha simulés dans cette étude, soit 24.5% de moins. Par conséquent, si on prend en compte un facteur de perte en eau de 30% et une surface de piste 24.5% supérieure, le besoin en eau simulée par cette étude est 4.8 Mm³ en 1995 (contre 4.8 Mm³) et 10.8 Mm³ en 2007 (contre 15.2 Mm³) soit des facteurs de 1 à 1.4 entre nos estimations et celles de Badré et al. (2009) et ODIT (2009). Ces écarts nous semblent très raisonnables dans la mesure où notre approche est très généraliste et que plusieurs sources significatives d'incertitudes existent, comme les pertes en eau lors de la production de neige.

Conclusion Nous avons exposé ici une méthode originale pour l'étude des interactions entre les conditions d'enneigement dans les domaines skiables français et des indicateurs socio économiques de leur activité. Cette méthode s'appuie sur des éléments structurants des domaines skiables (RM, taille, altitude) et fournit des simulations des conditions d'enneigement qui prennent en compte les spécificités géographiques des domaines skiables et les impacts physiques du damage et de la neige de culture sur les propriétés du manteau neigeux. L'altitude de viabilité de l'enneigement a été calculée sur la période 1958 - 2014 avec une moyenne en neige damée de 1480 m dans les Alpes du Nord et 2035 m dans les Alpes du Sud. Un second indicateur a été calculé qui prend en compte les spécificités des domaines skiables et notamment la répartition spatiale des enneigeurs au sein des domaines. Cet indicateur baptisé "vacances combinées" repose sur la viabilité de l'enneigement au cours des vacances de Noël et au cours des vacances scolaires d'hiver. Cette étude a montré qu'un poids relatif de 17% aux vacances de Noël et 83% aux vacances scolaires d'hiver fournit la meilleure corrélation aux journées skieurs sur la période 2001 - 2014. Cette étude a révélé une variabilité spatiale et temporelle importante de cet indicateur. Les besoins en eau et en énergie pour la production de neige de culture ont été calculés pour l'ensemble des 129 stations traitées dans cette étude sur la période 1985 - 2014 en prenant en compte l'évolution du taux d'équipement en enneigeurs au cours de cette période. Notre méthode semble sous estimer ces besoins, ce qui peut sans doute s'expliquer, au moins en partie, par une surface de piste simulée moins importante que les relevés existants et la non prise en compte des pertes en eau lors du processus de fabrication de neige de culture. Dans l'ensemble cette méthode a montré sa capacité à fournir des éléments fiables et pertinents, corrélés à l'activité économique des stations de sports d'hiver (journées skieurs) et permettant d'estimer les besoins associés en eau et en énergie pour la production de neige de culture grâce à une analyse rétrospective (1958 - 2014) des conditions d'enneigements dans les stations des Alpes françaises.

1.6 Conclusion générale

Ce travail de thèse a démarré sur un constat initial de méconnaissance des pratiques de gestion de la neige dans les domaines skiables et des variables pertinentes pour les activités de sports d'hiver par le milieu scientifique. Réciproquement les acteurs professionnels (gestionnaires, techniciens) et institutionnels (élus) rencontraient des difficultés pour s'appropriier les résultats issus de travaux de recherche pour l'évaluation des opportunités et des risques associés aux évolutions techniques (neige de culture) et climatiques (changements climatiques) en lien avec les sports d'hiver. L'objectif de ce travail consistait donc à questionner les interactions entre les conditions d'enneigement, variables dans le temps et l'espace et peu prévisibles, et les activités des stations de sports d'hiver, aux exigences et

aux contraintes fortes.

Cette étude s'est par conséquent attachée dans un premier temps à définir les attentes des opérateurs de domaines skiables en termes d'enneigement, les méthodes employées pour y parvenir et les moyens à leur disposition pour les réaliser. Dans un second temps, l'impact physique des ces actions humaines sur les propriétés du manteau neigeux (damage, production de neige) a été observé au cours de plusieurs campagnes de terrain et intégré dans un modèle physique de simulation des conditions d'enneigement. Ces deux approches complémentaires ont constitué les piliers de ce travail de thèse et apporté des éléments pour le développement d'une chaîne de modélisation physique des conditions d'enneigement dans les domaines skiables. Cette approche permet de prendre en compte la dynamique interactive entre les contraintes et attentes opérationnelles liées à la gestion de la neige et les impacts physiques de ces opérations sur l'évolution du manteau neigeux tout au long de la saison hivernale. Enfin, cette chaîne de modélisation a pu être couplée à une approche géographique et structurelle des domaines skiables, applicable à l'ensemble des domaines skiables des Alpes françaises. Ceci a permis le développement d'une méthode intégrée de simulation des conditions d'enneigement dans les stations de sports d'hiver fondée sur une approche opérationnelle de la gestion de la neige, une prise en compte physique de cette gestion sur l'évolution saisonnière du manteau neigeux et des caractéristiques individuelles des domaines skiables (taille, altitudes, pentes, etc.). Cette approche systématique ouvre un large champ de possibles pour la détermination d'indicateurs objectifs et pertinents sur les conditions d'enneigement pour des études prospectives de l'activité socio-économique de l'industrie du ski. Le potentiel et la fiabilité de cette méthode ont été évalués et discutés dans une analyse rétrospective de la vulnérabilité des domaines skiables des Alpes françaises aux conditions d'enneigement au cours de la période 1958 - 2014. L'évolution des besoins en eau et en énergie pour la production de neige de culture a également été modélisée et évaluée. Cette approche pourrait donc être employée pour l'analyse de la vulnérabilité des domaines skiables dans d'autres massifs montagneux que les Alpes. Les résultats issus de ces travaux pourraient ainsi être communiqués aux milieux professionnels afin d'en conforter et réévaluer la pertinence en termes d'indicateurs et d'en confronter les résultats à l'expérience vécue des opérateurs de domaines skiables. Ce travail d'appropriation de la méthode et de ses indicateurs par le monde professionnel fournira un cadre solide pour des analyses prospectives, notamment des effets attendus du changement climatique sur l'activité des stations de sports d'hiver et/ou des évolutions des équipements de neige de culture.

General introduction

In 2015, an important investment plan was announced after new representatives were elected in the “Auvergne Rhône-Alpes” region, to secure the snow reliability and related employment in ski resorts through snowmaking facilities. Many opponents criticized this plan arguing this neglected the mountains economy outside ski resorts and questioned the relevance of such methods regarding the projected changes of the climate and associated difficulties for the ski industry. This debate revealed the wide range of concerns related to the ski industry which policy makers and ski resorts stakeholders have to cope with for a long time. The weaknesses, strengths, threats and opportunities for the ski industry may be social, economic, environmental or climatic resulting in a complex equation which balance is and will remain a political decision.

A young industry After the second world war, the traditional agriculture of mountain regions faced an unbalanced competition with the extensive agriculture encouraged by the recently imported industrial model by Henry Ford, resulting in a large decrease in mountains populations. The opportunity for a complete change in the activity of French mountain regions appeared with the increasing demand for mass tourism in the 1950's (Francois and George-Marcelpoil, 2012). The first generation of ski areas (Chamonix, Megève, Val d'Isère) experienced a large success and resorts dedicated to skiing were created in high elevation areas where no villages originally existed (La Plagne, Isola 2000, Les Arcs, etc.). The building of real estate provided the funding for ski lifts facilities which in return ensured the attractiveness of ski resorts (Fablet, 2013). Supported by a steady growth, the ski industry became in the middle of the 1980's a major actor in the economy of mountain areas in France. In 2014, 20% of the Gross Domestic Product of the French departments of Savoie and Haute-Savoie were realized in winter tourism (Lecuret et al., 2014). Nowadays ten out of the thirty largest ski resorts in the world are located in the French Alps and France is a top ranked destination for worldwide skiers (Abegg et al., 2007; Vanat, 2014).

Structural weaknesses The dependence of the ski industry on the construction of real estate was revealed in the late 1980's when the renewal of ski lifts facilities and tourism urbanisation, encouraged by the 1992 Olympics in Albertville, required further constructions (Fablet, 2013). The accommodation capacity of resorts became oversized compared to ski lifts facilities requiring additional ski lifts, and involving ski resorts in a never-ending cycle of real estate construction (Pascal, 1993). In the meantime the occurrence of consecutive seasons with poor snow conditions (1989,1990,1993) showed the vulnerability of winter tourism to snow conditions because of the exclusive development of the skiing activity (Lorit, 1991). Since then, ski resorts steadily invested in snowmaking facilities to mitigate the impacts of the natural variability of the climate on their activity.

Observed changes of the climate The investments by ski resorts in snowmaking facilities enhanced after the climate change was shown as an international concern by the first international conferences of the United Nations on climate changes²⁰. Snowmaking was actually the main argument of ski resort to promote their capacity to cope with and anticipate the impacts of climate changes (Trawöger, 2014). The Intergovernmental Panel on Climate Change (IPCC) compiled a wide range of investigations on climate changes and confirmed the responsibility of human societies in many of these changes, particularly regarding the outstanding increase in the greenhouse gases (GHG) concentrations in the atmosphere since 1950 (Figure 1.1). The observed global warming between 1880 and 2012 of the mean

²⁰ The third conference of the United Nations Framework Convention on Climate Change was held in Kyoto in 1997 and provided a reference international protocol on climate concerns.

air temperature was computed within a 90% probability range of +0.65 to +1.06°C, with an average value of +0.85 °C (IPCC, 2014). Gobiet et al. (2014) estimated that the mean air temperature in the European Alps has increased from the late 19th century of an average +2°C i.e. a rate twice higher than the global rate. Durand et al. (2009b) calculated a similar value and estimated that the mean air temperature in the French Alps has increased by +1.15°C between 1958 and 2002. In the meantime most investigations on the amounts of precipitations concluded to a large variability in space and time without any statistically significant change (Beniston, 2006; Gobiet et al., 2014). The evolution of snow conditions has therefore mostly been influenced by the air temperature which governs in particular the elevation of the limit between snow and rain precipitations. The increase of the air temperature would rise this limit to higher elevations with less snow and shorter seasons with snow on the ground at lower elevations (Durand et al., 2009a; Marty, 2013). As an example, the season duration at the Col de Porte observation site in Chartreuse, France (1325 m.a.s.l) diminished by 6 days per decade on average during the 1960 - 2012 period and the average snow depth between the 1 December and 30 April by 13 cm per decade (Lesaffre et al., 2012). All scientific investigations on climate change agree on the trend of changes i.e. an increase in the air temperature and a decrease in snow conditions although the magnitude of the impacts differs between regions and elevations (Gilaberte-Búrdalo et al., 2014; Gobiet et al., 2014).

Projections The 2014 IPCC report considered four distinct Representative Concentration Pathways (RCP) regarding the evolution of greenhouse gases concentrations in the atmosphere over the 21st century. The RCP include two options assuming a steady growth in global populations and economic activities without specific policies regarding GHG emissions (RCP6.0 and 8.5), an option assuming the stabilization of GHG emissions by the mid century (RCP4.5) and a fourth option assuming a significant decrease of GHG emissions (RCP2.6). According to the IPCC report, an increase of the mean air temperature limited to +2°C corresponds to a cumulated emissions of 2900 GtCO₂ of GHG²¹ since the pre industrial era, given that 1900 GtCO₂ cumulated emissions were estimated in 2011 (IPCC, 2014). The only option that allows limiting the global warming to a maximum +2°C in the late 21st century is the most optimistic option RCP2.6. Since the climate is a highly inertial system, all RCPs project similar evolutions of the mean air temperature for the 2020 - 2050 period with an increase ranging between +0.3 and +0.7°C with respect to the 1986 - 2005 period (IPCC, 2014). Mountain areas will suffer higher evolutions of the temperature with a projected minimum increase of +1.5°C over the 2021 - 2050 period compared to the reference 1961 - 1990 (Rousselot et al., 2012; Gobiet et al., 2014). Snow conditions will be impacted at all elevations and particularly below 1500 to 2000 m.a.s.l (Rousselot et al., 2012; Kotlarski et al., 2012; Marty, 2013). Abegg et al. (2007) estimated that the elevation encountering 30 cm deep snow for 100 days or more would rise by 150 m per degree Celsius of increase of the mean air temperature. Rousselot et al. (2012) computed the average snow depth in December, January and February and concluded this would decrease by a minimum 30% over the 2021 - 2050 period compared to 1961 - 1990. Such projected evolutions combined with the experience by ski resorts of their own vulnerability to poor snow conditions raised the interest of resorts stakeholders and policy makers for prospective data on the potential impacts of climate change on the ski industry.

Interactions between climate and human activities Providing relevant and reliable data on the impact of climate change on human activities is a major challenge for the scientific community due to the dynamics of interactions between meteorological and snow conditions with winter tourism activities

21. 1 GtCO₂, or 1 million tons of equivalent CO₂ (IPCC, 2014).

(snow management, economic revenue). The investigations developed during the course of this PhD project focus on these interactions (Figure 1.26) between snow conditions (variability, low predictability) and human activities (defined by purposes and means) by means of two distinct and complementary approaches. Firstly, the objectives pursued by operators, the means they employ (grooming, snowmaking) and constraints they face (meteorological, structural or organization issues) in daily operations have been investigated to provide a synthesis of snow management operations in French ski resorts which can be used for modelling purposes (chapters 2 and 3). Secondly, a physically based modelling approach of the impact of grooming and snowmaking on snow properties was developed in the snow model Crocus and evaluated with respect to field observations over two consecutive winter seasons (chapters 4 and 5). These two components were integrated with a socio economic database of ski resorts to provide an explicit spatial modelling of managed snow conditions on ski slopes for the entire French Alps ski resorts. Such method allowed defining snow reliability indicators which relevance and reliability were discussed in a retrospective analysis on the 1958 - 2014 period (chapter 6).

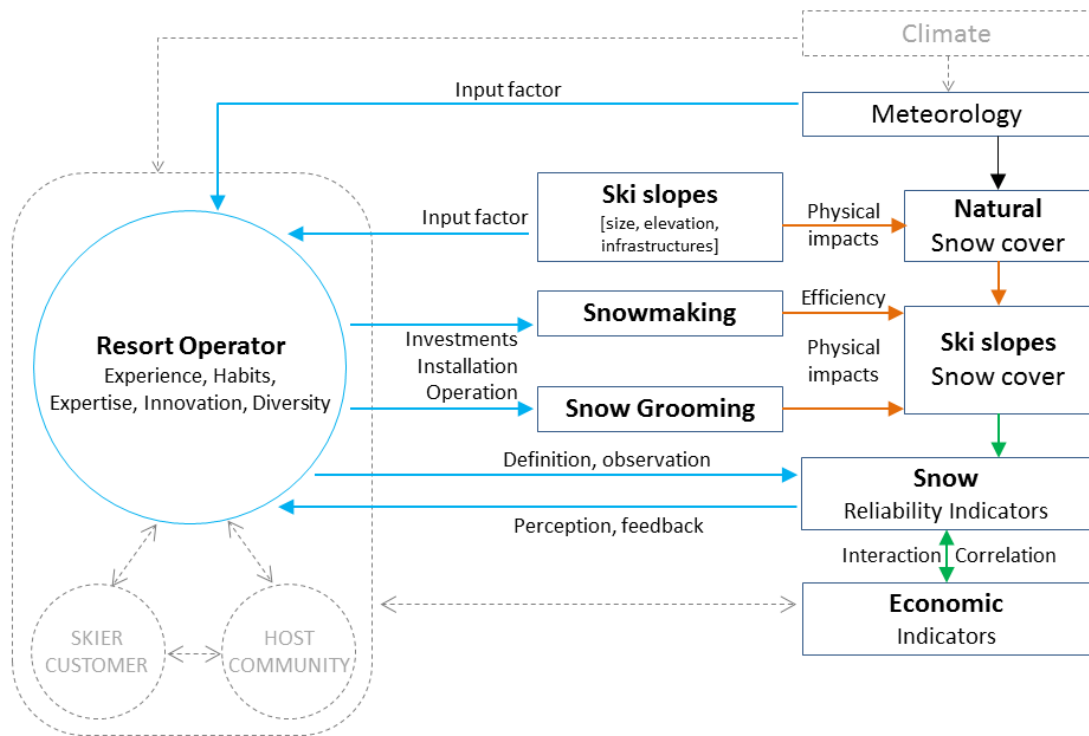


FIGURE 1.26 – Scope of the present PhD. Blue interactions correspond to human approaches of snow management (Chapters 2 and 3). Orange interactions correspond to the physical impacts of snow management on the snowpack properties (Chapters 4 and 5). Green interactions correspond to the design and application of relevant snow reliability indicators for socio economic investigations on ski resorts (Chapter 6). Grey curve are interactions of major interest which are not covered by the present work.

Première partie

Professional approaches of snow management in French ski resorts

Chapitre 2

Panel based assessment of snow management operations in French ski resorts

This chapter corresponds to the paper by Pierre Spandre, Hugues François, Samuel Morin et Emmanuelle George-Marcelpoil, 2016. "Panel based assessment of snow management operations in French ski resorts", *Journal of Outdoor Recreation and Tourism* doi 10.1016/j.jort.2016.09.002

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2.1 Introduction

Ten out of the thirty greatest ski resorts in the world are located in the French Alps leading the French ski industry to be a top ranked destination for skiing activities along with Austria, U.S.A, Italy, Switzerland or Canada (Abegg et al., 2007; Vanat, 2014). Therefore, winter tourism is a major industry and plays a fundamental role in the economy of French mountain regions (Falk, 2014; Lecuret et al., 2014). In the Savoie Mont Blanc area¹, 20% of the gross domestic product (GDP) of the departments is generated by the winter tourism (Lecuret et al., 2014). Skiing is the most practiced activity in winter (83% of visitors), far above the second (snowshoeing, 16% of visitors) leading the ski resorts operators to pay a great attention to skiing conditions and driving the corporation to an increasingly technical and professional snow management (Lecuret et al., 2014; Fauve et al., 2002).

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

Concurrently with the snowmaking expansion, the economy of snow-related activities has been discussed in present time and under future potential climate conditions using several indicators such as the ski lifts tickets sales (Falk, 2014; Koenig and Abegg, 1997), the overnight stays of consumers in ski resorts (Falk, 2010; Töglhofer et al., 2011) or in terms of contribution to the gross domestic product (Damm et al., 2014). A major challenge of researchers intending to assess the vulnerability of snow-related economy to climate change is to associate these indicators with climate dependent factors such as the mean snow depth (Falk, 2014), the number of days with snow on the ground (Töglhofer et al., 2011), with a minimum snow depth (Scott et al., 2003; Schmidt et al., 2012; Hanzer et al., 2014; François et al., 2014) or snow mass (Marke et al., 2014). Due to the difficulty to combine such transdisciplinary approaches (Strasser et al., 2014) and to compare the results from different combinations of indicators (Neuvonen et al., 2015), a standard definition of the snow reliability of ski resorts was established, combining snow depth and season length, the so-called "100 days" rule (Elsasser et al., 2002; Scott et al., 2003). This was used to address the snow reliable altitude of a region (Elsasser et al., 2002; Abegg et al., 2007), the decline of the ski season length due to climate change or the required amounts of machine made snow to compensate the loss (Scott et al., 2003; Steiger, 2010) even though the required snow depth may depend on the region (Scott and McBoyle, 2007; Pons-Pons

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

et al., 2012) or on the period of the season (Hennessy et al., 2007; Hanzer et al., 2014; Damm et al., 2014). The adaptation of the ski industry to climate change through snowmaking has been studied in Australia (Hennessy et al., 2007), New-Zealand (Hendrikx and Hreinsson, 2012), Andorra (Pons-Pons et al., 2012), Spanish and French Pyrenees (Pons et al., 2015), Germany (Pröbstl, 2006; Schmidt et al., 2012), Switzerland (Rixen et al., 2011), Austria (Steiger, 2010; Töglhofer et al., 2011; Damm et al., 2014), U.S.A (Dawson and Scott, 2013) and Canada (Scott et al., 2003; Scott and McBoyle, 2007).

Surprisingly French and Italian Alps are major areas within the international skiing market where little investigation has been undertaken and has been limited to the analysis of past conditions and under natural snow conditions (Elsasser et al., 2002; Abegg et al., 2007; François et al., 2014). Until recently there was no snowpack model able to handle snow production or grooming over the French Alps (Spandre et al., 2016c) in addition to the prohibitive lack of information on snowmaking facilities in ski resorts (François et al., 2014). To the best of our knowledge there is no publication describing the French grooming facilities and practices, and the latest investigation on snowmaking facilities is limited to the ratio of equipped ski slopes with snowguns aggregated at the national level and based on data from the 2007 - 2008 winter season (Badré et al., 2009). Such limitations hampered any investigation, either in the past or under future climate projections, of snow conditions in French ski resorts accounting for snow management which require more detailed information on professional practices (Scott and McBoyle, 2007; Hanzer et al., 2014; Spandre et al., 2016c). The present study therefore aims to question the general priorities of French ski resorts operators and how these influence their habits and facilities in terms of snow management with respect to the existing international data (Scott et al., 2003; Abegg et al., 2007; Hennessy et al., 2007, Section 2.2). We also provide detailed information on the snowmaking and grooming facilities (ratio of equipped ski slopes, snowguns types, water storage capacity) and practices (grooming frequency, snowguns positioning, required snow depth regarding the date) in French ski resorts with respect to their characteristics (altitude, size and location).

Our analysis is based on a survey of a panel of 55 French ski resorts carried out in autumn 2014 and a specific database on French Alps ski resorts, allowing the analyze of the survey's results based on resorts features (Section 2.3). We identify the main priorities of ski resorts operators and the main drivers of the current practices and facilities in terms of grooming and snowmaking (Section 2.4), including their potential evolution until 2020. Last, we discuss the relationships between the vulnerability to natural snow conditions from François et al. (2014) of sample ski resorts and their current level of equipment in snowmaking facilities with respect to their main features, intending to provide a synthesis framework for the analysis of the development of snowmaking facilities within French ski resorts (Section 2.5). The limitations of the survey's setup and results are also discussed.

2.2 Literature review

2.2.1 Grooming impact and interest for stakeholders

The grooming of ski slopes is a fundamental method for the preparation of ski slopes shared by almost all resorts (Fauve et al., 2002). Grooming significantly affects the snowpack properties (Keddy, 1979; Fahey et al., 1999; Keller et al., 2004; Rixen et al., 2004; Mossner et al., 2013; Howard and Stull, 2014; De Jong et al., 2015). Fahey et al. (1999) monitored four groomed slopes and found that the average density was 36% higher on groomed slopes with respect to control slopes (ungroomed). Mossner et al. (2013) reported values from 344 measurements of snow density on ski slopes ranging between 420 and 620 kg m⁻³ with a mean value of 556 kg m⁻³. Since the snow thermal conductivity

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

2.2.2 Variability, climate change and snowmaking

Durand et al. (2009b) analyzed 47 years of climate conditions from a combined approach of modelling and observations and outlined a significant spatial and temporal variability of the natural snow conditions in the French Alps. This variability was found maximum for mid-alitudes, about 1500 m.a.s.l. Such variability of the snow conditions was also reported in the European Alps (Gobiet et al., 2014; Beniston, 1997) or in North America (Hughes and Robinson, 1996). Most projections of the impact of climate change also indicated that the interannual variability is likely to remain very significant in coming decades (Rousselot et al., 2012; Castebrunet et al., 2014; Kotlarski et al., 2014; Marke et al., 2014). François et al. (2014) investigated the natural snow conditions in French Alps ski resorts accounting for the geographical features of resorts (altitude, slope aspect) and calculated a viability index as the share of the ski area encountering more than 30 cm of snow for at least 100 days. The viability of small resorts ranged between 18 and 90% while very large resorts showed viability index between 65% and 97% over the 2001 to 2012 decade. The vulnerability of ski resorts to the variability of the natural snow conditions were confirmed in all alpine countries (Elsasser et al., 2002; Abegg et al., 2007). Falk (2010) estimated from a panel of 28 Austrian resorts and for the period 1986 - 2005 that the number of visitors in resorts with ski slopes below an altitude of 2000 m.a.s.l decreased with snow depth even though snowmaking mitigated the magnitude of the impact. On the base of a large panel of Austrian ski resorts and over a long period of time (1972 - 2007), Töglhofer et al. (2011) estimated that a one standard deviation increase in snow conditions (mean snow depth, days with snow on the ground and days when snow depth exceeds 30 cm) leads to a 0,6 to 1,1% increase in overnight stays. Similarly to Falk (2010), this relationship was highlighted for resorts with a mean altitude below 1800 m.a.s.l. otherwise a negative relationship was found. Concurrently, Trawöger (2014) concluded from interviews of 24 experts (CEOs of tourism associations or cable car companies) in the Austrian Alps that the dependency to natural snow conditions was the major driver of the development of snowmaking in ski resorts and Hopkins (2015) highlighted the same role of snowmaking in interviews of a sample of 14 ski industry stakeholders in the region of Queenstown (New-Zealand). In 2005, 16% of ski slopes were equipped with snowmaking facilities in France, 50% in Austria, 18% in Switzerland and 40% in Italy according to Abegg et al. (2007). This ratio may have risen in 2015 to 32%, 70%, 48% and 70%

respectively in France (Spandre et al., 2015), Austria, Switzerland and Italy (Seilbahnen Schweiz, 2015). However Hopkins and Maclean (2014) concluded from interviews of stakeholders in five ski resorts in Scotland that some regions were not able to produce machine made (MM) snow (Fierz et al., 2009) due to inadequate meteorological conditions.

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

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

2.2.3 Snow management processes

Most investigations of snow management built up synthetic approaches to govern snowmaking to estimate the required amounts of machine made snow to achieve satisfying skiing conditions, particularly regarding the impacts of climate change (Scott et al., 2003; Scott and McBoyle, 2007; Steiger, 2010). Since most snow models that have been used can not account for the impact of grooming, little attention has been paid to model the grooming process (Scott et al., 2003; Steiger, 2010; Pons-Pons et al., 2012; Hanzer et al., 2014). Beyond modelling physical processes within the snowpack (Howard and Stull, 2014; Spandre et al., 2016c), distinct frameworks (periods of production, snow-base layer)

and thresholds (triggering temperature and snow depth) have been used to model the snowmaking process. Scott et al. (2003); Scott and McBoyle (2007); Steiger (2010); Pons-Pons et al. (2012) used the dry-air temperature to control the production decision (threshold of -5°C or -2°C) and Rixen et al. (2011) the dew-point temperature (threshold of -4°C) while the most relevant meteorological parameter which is used by professional snowmakers is the wet-bulb temperature T_w (Olefs et al., 2010; Hanzer et al., 2014; Spandre et al., 2016c). The technical threshold indicated by snowguns manufacturers is $T_w = -2^{\circ}\text{C}$ (Olefs et al., 2010; Hanzer et al., 2014) while practices by professional snowmakers may differ (Hendrikx and Hreinsson, 2012; Spandre et al., 2016c).

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

Based on a survey of a sample of 55 French ski resorts (Section 2.3), the present study therefore questions the general priorities of stakeholders and provides detailed information on snowmaking and grooming facilities in the French Alps (Section 2.4). We further discuss how the priorities pursued by stakeholders drive the current practices and facilities in terms of snow management and the relevance of these relationships regarding resorts features, including their vulnerability to natural snow conditions from François et al. (2014), intending to provide a synthesis framework for the analysis of the development of snowmaking facilities within French ski resorts (Section 2.5).

2.3 Methods and definitions : structural data on ski resorts and treatment of survey’s results

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

An online survey towards professionals was set up in Autumn 2014 and sent to 161 contacts of managers of technical services of ski resorts. The national association of ski patrol managers (ADSP, standing for “Association Nationale des Directeurs de Pistes et de la Sécurité des stations de Sports d’Hiver”) provided these contacts. A code was dedicated to every contact to guarantee a personal access to the survey as well as the confidentiality of data. The survey was closed on 9 January 2015.

Data from the socio-economic database “BD Stations” (Marcelpoil et al., 2012) were used to assess the representativity of the survey’s sample among all French Alps resorts and to analyze the survey’s results. The “BD Stations” is a powerful tool to support investigations focused on large territories where winter sports are an activity among many others or zoomed at the scale of a single ski-lift (François et al., 2014; Spandre et al., 2015). The database includes geographical representations of ski slopes surfaces named “gravitational envelopes” (Francois et al., 2016) and structural data on ski lift referred to as the ski-lift power (SLP) and defined as the product of the elevation difference between the bottom and the top of a ski lift (in km) and its flow of persons per hour (pers h⁻¹). The aggregated SLP of a ski resort is a relevant indicator of its size which is used by “Domaines Skiabiles de France” (DSF), the French national association of ski resorts to distinguish four resorts categories (Table 6.1 and François et al. (2014)).

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

TABLE 2.1 – Ski resorts categories regarding the ski lift power (François et al., 2014)

2.3.2 Treatment method of the survey’s results

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

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

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

2.3.3 Diversity and representativity of the sample ski resorts

56 ski resorts participated to the survey. 18 of them participated the day of the general assembly of the ADSP association, on the 7 October 2014. Most participant ski resorts are located in the French Alps : 11 in the Southern Alps² and 33 in the Northern Alps³ among which 21 located in Savoie (73). Consistently with the distribution of ski resorts in French mountain regions, 8 participant ski resorts are located in the Pyrenees⁴, two in the Jura⁵, one in the Massif Central⁶ and one in the Vosges⁷.

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

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

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

5. Department Jura (39).

6. Department Cantal (15).

7. Department Vosges (88).

Since the ski resort located in Andorra does not depend on the STRMTG national service (“Service Technique des Remontées Mécaniques et des Transports Guidés”), no data were available in the “BD Stations” to analyze its answers and we could not account for its results.

Resorts categories	Small resorts (S)	Medium resorts (M)	Large resorts (L)	Very Large resorts (XL)
Ski slopes surface (ha)	70 ± 36	99 ± 44	172 ± 98	437 ± 254
Ski slopes length (km)	37 ± 20	64 ± 29	122 ± 56	221 ± 105
Ski slopes width (m)	20 ± 8	18 ± 8	16 ± 9	20 ± 10
Average Age of ski-lifts (years)	26 ± 10	23 ± 8	19 ± 8	20 ± 5
Average Altitude of ski-lifts (m.a.s.l)	1480 ± 600	1810 ± 450	1910 ± 550	2180 ± 500
Ski lift power (SLP, km pers h ⁻¹)	1350 ± 870	3900 ± 1330	8250 ± 5250	24600 ± 11260

TABLE 2.2 – Average characteristics of ski resorts which participated to the survey, weighted by the SLP (± the standard deviation). The age, altitude and ski lift power data from the “BD Stations” database.

The 55 resulting resorts represent 25% of the 220 French ski resorts in total (DSF, 2011), only 5% of the French small resorts (S) are represented against 38% of the medium, 65%, of the large (L) and 62% of the very large resorts (XL). Even though the majority of French ski resorts are small, their aggregated SLP is low compared to the other categories (7% of the national SLP, 2% of the sample SLP). The sample of ski resorts participating to the survey represents 51% of the French total SLP. There is a large dispersion of the SLP, average age and altitude of ski resorts within each category (Figure 2.1, Table 2.2) which Spandre et al. (2015) showed to be consistent with the dispersion within the total population of alpine resorts for each category (Marcelpoil et al., 2012) suggesting that the results of this survey can be considered in a large extent as representative of the French ski resorts.

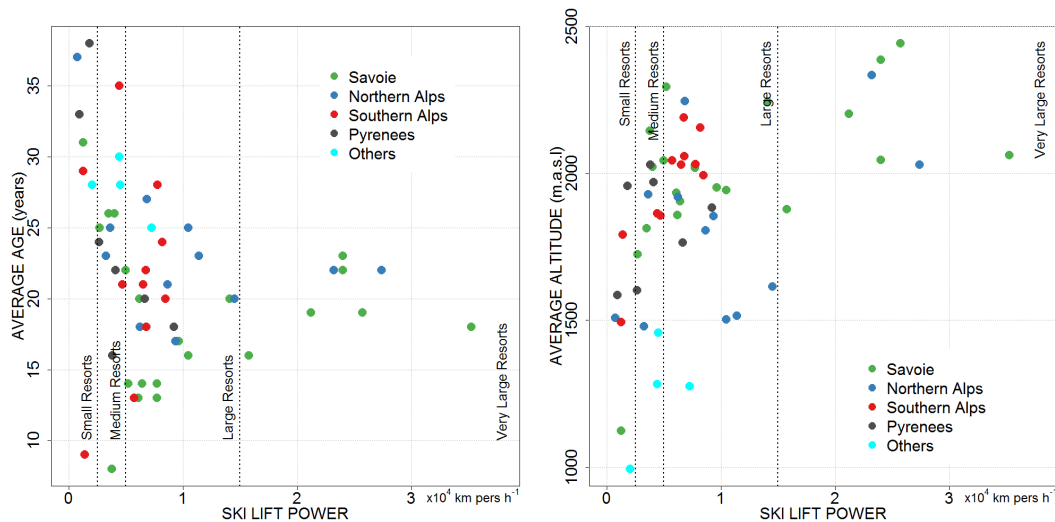


FIGURE 2.1 – Average Age and Altitude of ski-lifts of the participant ski resorts. Data from the “BD Stations” database. The category “Northern Alps” includes here all resorts in the northern Alps outside Savoie i.e. in Isère and Haute-Savoie (N = 12 resorts). “Others” includes here the resorts from Jura, Cantal and Vosges of the sample ski resorts (N = 4).

2.3.4 Description of the ski fields of the sample ski resorts

There is a significant relationship between the ski-lift facilities of a ski resort (SLP) and the offer in terms of potential surface of ski slopes (Table 2.2) : the ratio of the skifield surface to the SLP of a resort proves relatively stable for the largest categories (M to XL) with $0.020 \text{ ha (km pers h}^{-1})^{-1}$. The average altitude and age of ski-lifts are also related to the size of a ski resort : the larger the resort, the higher and the more recent the ski-lifts (Figure 2.1 and Table 2.2). This relationship can also be noticed in the geographical pattern of the sample ski resorts : 6 out of the 8 very large resorts are located in Savoie and the 16 largest resorts of the sample are located in the Northern Alps (Figure 2.1). The average ski-lift power of sample ski resorts located in Savoie is $11\,400 \text{ km pers h}^{-1}$ and respectively $10\,500$, 5600 , 4200 and $4600 \text{ km pers h}^{-1}$ in the Northern Alps outside Savoie, in the Southern Alps, in the Pyrenees and in the other mountains of France. In Savoie, the average age of ski lifts is 18.7 years old and the average altitude of sample ski resorts is 2110 m.a.s.l. In the Alps (outside Savoie) and in the Pyrenees, the average age of ski lifts range between 21 and 22 years old and average altitude between 1860 and 2020 m.a.s.l. The four resorts located in the other mountains of France have an average age of 27 years old and an average altitude of 1290 m.a.s.l. The sample of ski resorts outlines the strong geographical pattern of ski resorts in France : the largest French ski resorts benefit from the youngest ski lifts in the highest areas and are first located in Savoie then in the rest of the Northern Alps and last in the Southern Alps, the Pyrenees and other mountains of France.

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

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

Distinct patterns between categories may also be revealed by the perception by ski resorts operators of their own economic situation and vulnerability to snow conditions (Figure 2.2). In the case of small resorts, the economic situation is seen as related to the snow conditions while for a given perception of the snow conditions the medium resorts indicate contrasted perceptions of the economic situation of their resort. For example, nine medium resorts indicate that the average snow conditions are “Good”, three of them think the economic situation of the resort is “Weak” and two estimate it is “Very Good”. In the case of large resorts, they do not perceive significantly better snow conditions compared to medium resorts but the economic situation is one step better (“Fair” as a minimum). A similar analysis can be drawn from the answers of very large resorts : they do not have a better perception of their own snow conditions than large or even medium resorts but the economic situation is seen as “Good” or “Very Good”. Consistently with the diversity in resorts characteristics, their perception of the economic situation and vulnerability of the resort to snow conditions appear constricted.

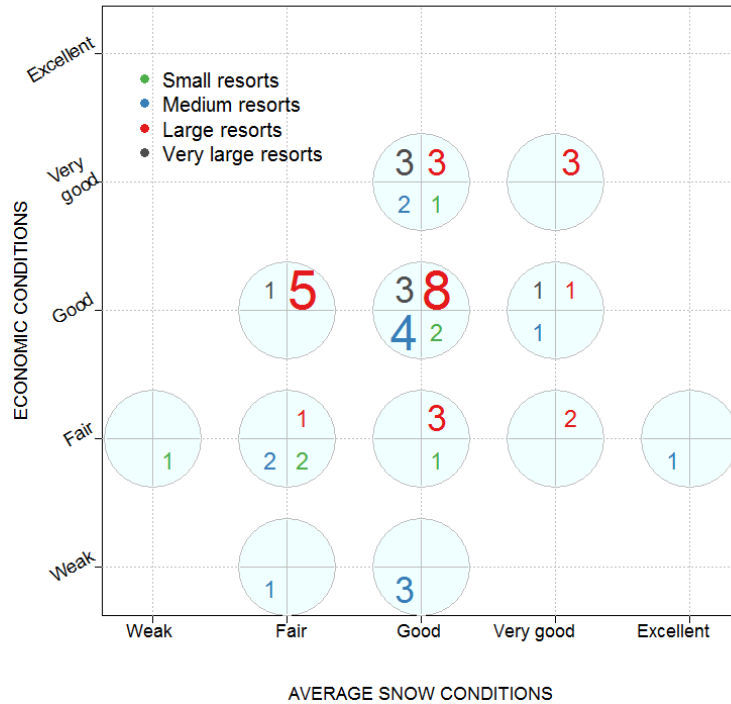


FIGURE 2.2 – Perceptions of the economic situation of the ski resorts vs. the perceived snow conditions by ski resort operators. For each category the number of resorts is indicated with a proportional size of the marker.

2.4.2 General priorities of resorts stakeholders

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

Such priorities provide a background for the interpretation of most practices of grooming and snow-

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

2.4.3 Grooming operations and facilities

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

Optimization of grooming operations Over two thirds of the sample ski resorts indicated that they intend to reduce grooming costs either by enhancing the process efficiency (faster grooming, technological innovations, etc.) or reducing the surface of groomed ski slopes. Concurrently 20% of ski resorts are equipped in 2015 with onboard measurements of the snow depth and 50% of the non equipped resorts consider it. In 2015, a majority of very large (75%) and a few large resorts (20%) are already equipped. Such systems help in optimizing not only the work done by grooming machines but more importantly the need for machine made snow that can be addressed from the difference between the measured snow depth and the required snow depth for skiing.

2.4.4 Managing the snow depth over the season : the driver for snowmaking

Driving snowmaking Maintaining a sufficient snow depth is as a major priority for skiing activities (mark 8.1/10) by ski resorts operators. The required snow depth for skiable conditions does not significantly depend on the size of the resort : small resorts indicate a minimum of 42 cm, medium resorts 49 cm and large and very large resorts a minimum 46 cm (average). Concurrently, ski resorts indicate that reaching a specific snow depth at a given date is not as important (mark 5/10 for small resorts, 6/10 for large resorts and 7/10 for large and very large resorts). However 49 of the participant ski resorts provided a specific snow depth and date to this question (Figure 2.3). Five of them focus on the early season (average target date on the 15 December, Figure 2.3).

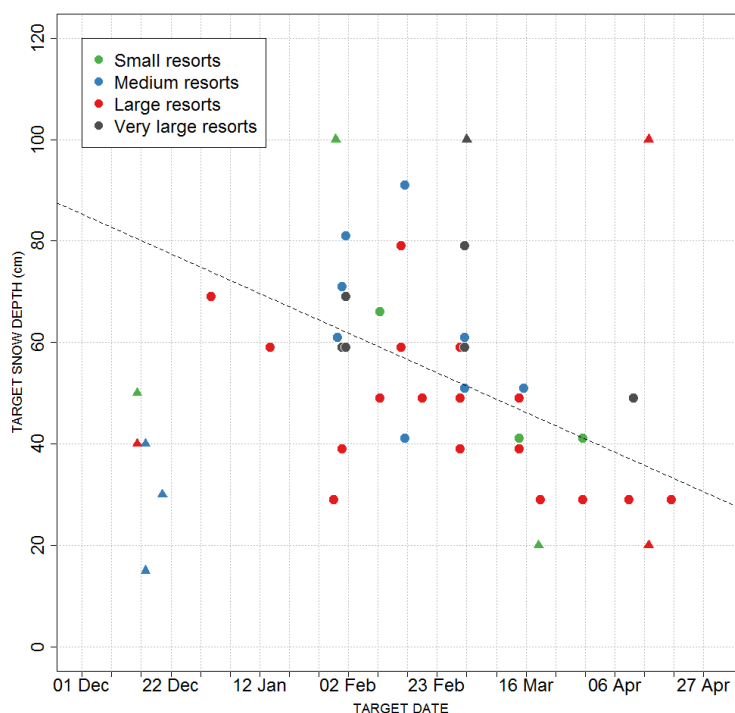


FIGURE 2.3 – The target snow depth versus the target date to reach it. The linear model does not account for the triangular points which we either related to opening constraints (December dates) or removed (maximum and minimum target snow depths, respectively 100 and 20 cm).

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

Interestingly, a geographical pattern exists for the 44 remaining answers with a stronger focus on the early February by sample ski resorts located in the Pyrenees (average target date on the 10 February, similar in Jura, Cantal and Vosges), on the heart of the winter season in the Northern Alps (24 February) and late season in the Southern Alps (12 March). These dates can be compared to the records of French academic holidays, available online since the 1960's (Ministère de l'Education Nationale de l'Enseignement Supérieur et de la Recherche, 2016). On average the Christmas and New Year holidays have begun the 20 December and ended on the 5 January (± 2 days, standard deviation). From the 1990's the French academic winter holidays have begun on average the 8 February and ended on the 9 March (± 4.5 days).

Triggering of snowmaking The wet-bulb temperature (combining the dry-air temperature and the air humidity) is used to trigger the production of MM snow (Olefs et al., 2010) with a technical threshold

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

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

2.4.5 Snowmaking facilities and production capacity with respect to ski resorts size

Current facilities Only one small resort among the 55 participant ski resorts does not have any snowmaking facilities and explains this is both a conviction and a commercial argument which constitutes an original approach. Otherwise, the medium to very large resorts are currently equipped at very similar levels, around 35% (Table 2.3). Small resorts are less equipped with about 18% of their ski slopes covered. Focusing on the location of resorts, the ratio of equipped ski slopes with snowmaking facilities is similar in the Northern Alps (32%), in the Pyrenees (31%) and in the Jura, Cantal and Vosges ski resorts (35%). This ratio is significantly higher in the Southern Alps (41%). Similarly to previous investigations (Badré et al., 2009) the survey confirms that air/water guns are preferred to fan guns in France (Table 2.3) with an average 2.5 to 3.1 snowguns per hectare of equipped ski slopes.

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

TABLE 2.3 – Current snowmaking facilities in ski resorts, by integrating results for each category (\pm the standard deviation).

Water supply The supply of water is ensured in most cases by specific reservoirs (Peyras et al., 2010) dedicated to MM snow production (Figure 2.4) : 38 ski resorts among the 54 which produce MM snow have built reservoirs for water storage. One third of these resorts (17 out of 54) have this only source of water for MM snow production : the reservoirs are probably filled with snowmelt water in summer and autumn (Marnezy, 2008). An additional 19 resorts combine it with drinking water supply (DWS) or natural waterways or both. The total reservoir volume with respect to the surface equipped with snowmaking facilities does not depend on the size of the resort (Table 2.3) : 1500 to 1800 m^3 of water

per hectare i.e. 150 to 180 kg of water per m² of equipped ski slope. The capacity of reservoirs in the 17 ski resorts of the sample where this is the only source of water is 190 kg of water per m² of equipped ski slopes with snowmaking facilities with a maximum of 390 kg of water per m².

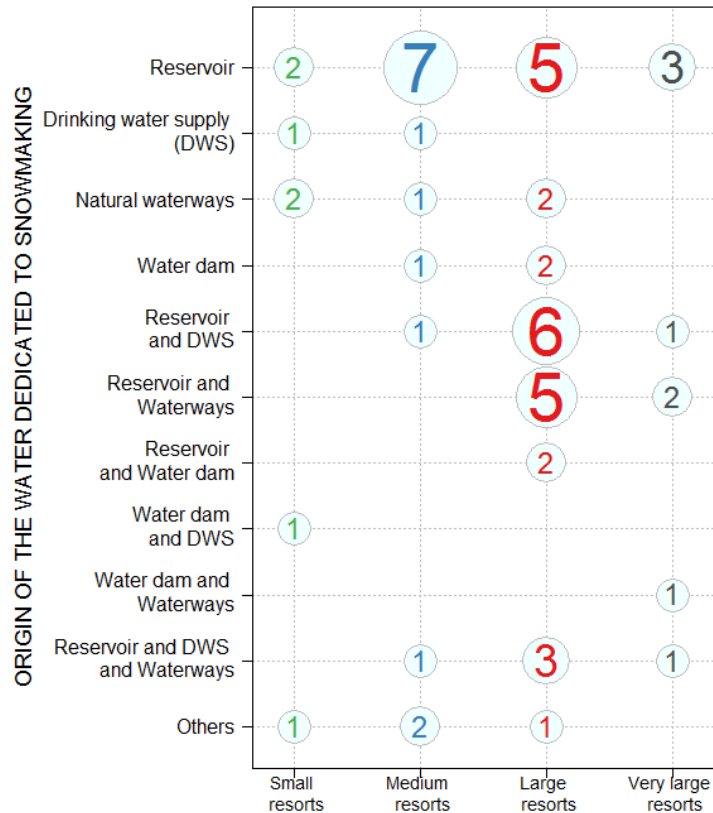


FIGURE 2.4 – Origin of the water dedicated to snowmaking. Reservoirs are defined as built exclusively to contain water for snowmaking purposes (Peyras et al., 2010) while water dams have usually been built for hydropower purposes. In such case snowmaking is a secondary goal. For each category the number of resorts is indicated with a proportional size of the marker.

Evolutions On one hand resorts operators intend to reduce the costs of snowmaking (over two thirds of the participant resorts), either by optimizing the production (85% indicate they record the volume of water used for production) or by increasing the process efficiency (automation, technological innovations, Hopkins (2015)), on the other hand most resorts indicated that they plan to extend their snowmaking facilities within an average five years (Table 2.4).

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

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

TABLE 2.4 – Likely snowmaking facilities in ski resorts in 2020. The surface of equipped ski slopes in 2020 was obtained by integrating results for each category (\pm the standard deviation). The year when the extension should be completed is a simple average of results (\pm the standard deviation).

The resulting surface equipped with snowmaking facilities (assuming the total ski field surface does not change) may reach 34 to 49% of the total ski field surface for respectively the small to very large resorts categories (Table 2.4). As long as all ski slopes are not entirely equipped with snowmaking, choices have to be made to spread out the facilities within the resort to guarantee the opening and closing dates and the way back down to the village by ski (section 2.4.2). A detailed description of the positioning of facilities and the criteria to trigger the production are provided in the following section.

Spatial positioning of snowguns The smaller the resort, the stronger attention is paid to the positioning of snowmaking facilities within the resort (Table 2.5). More than two thirds of the Small or Medium resorts indicated they gave priority to lower altitude areas while only 25% of Very Large did. Overall 30 resorts out of 54 indicated a maximum altitude for the installation of snowguns. This maximum altitude of snowmaking facilities (when provided) was plotted versus the average altitude of the ski-lifts of the resort from the "BD Stations" database (Figure 2.5). The slope of the linear model is 1.1 ($R^2 = 0.65$) i.e. the maximum altitude of snowmaking facilities is hardly higher than the average altitude of the ski-lifts for a given resort. The relationship is statistically significant (p -value = 10^{-7} , coefficient 0.81 in the 95% confidence interval) according to the Pearson's product moment correlation test (Onwuegbuzie et al., 2007). The analysis of preferred slopes (in terms of angular aspect) does not show any significant pattern (data not shown) : the preferred slopes depend on resorts local characteristics and stakeholders specify these slopes are "turned towards the village".

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

TABLE 2.5 – Priorities for the installation of snowmaking facilities in ski resorts. Average result (\pm the standard deviation)

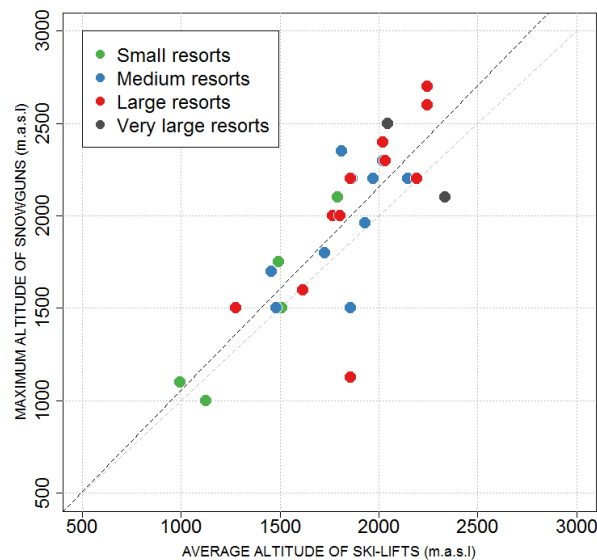


FIGURE 2.5 – The maximum altitude of snowguns (from the survey) versus the average altitude (from the “BD Stations” database) of the sample ski resorts. The dashed black line is the linear model of all answers (slope 1.1). The grey dashed line has a slope of 1.

2.5 Discussion

2.5.1 Identification of influential factors for the development of snowmaking facilities

Probability of occurrence The announced due dates for the extension of snowmaking facilities are relatively short (Table 2.4) regarding the planning of such projects in terms of economic investments (Damm et al., 2014), authorization processes, preliminary investigations and construction work (Peyras et al., 2010; Evette et al., 2011a) we therefore expect such evolutions to be very likely to occur by 2020.

Vulnerability to snow conditions : a driver amongst others Since all resorts experience contrasted natural snow conditions (Durand et al., 2009b; François et al., 2014) and pursue similar purposes (sections 2.4.2 and 2.4.4), thus we expected the snowmaking facilities to differ between resorts with respect to their vulnerability to natural snow conditions. We compared the viability index (natural snow) from François et al. (2014) (available for French alpine resorts only) to the ratio of equipped ski slopes with snowmaking facilities. The ratio of equipped ski slopes shows a negative relationship with the viability index although it is low (slope $-4.4 \cdot 10^{-2}$, Figure 2.6) and weak ($R^2 = 5 \cdot 10^{-4}$). The Pearson's product moment correlation test (Onwuegbuzie et al., 2007) confirmed the relationship was not significant (p -value = 0.87). We conducted tests on subsets limited to the ski resorts of each category without significant relationship either. An additional subset was considered by excluding points when the ratio of equipped ski slopes exceeded 50% or were below 10% (Figure 2.6, triangular points) consisting in 34 resorts (bullets). The slope of the linear model is -0.29 ($R^2 = 0.15$). The Pearson's product moment correlation coefficient of the sample (-0.398) is included in the 95% confidence interval (p -value = 0.02) confirming a statistically significant relationship. The location of ski resorts also provides an interesting pattern : the average viability index of ski resorts are 83% and 65% in respectively the Northern and Southern Alps ski resorts (period 2001 - 2012) while the average ratio of equipped ski slope with snowmaking facilities are respectively 32% and 41% (Section 2.4.5). The analysis of the ratio of equipped ski slopes versus the vulnerability to snow conditions revealed a poor relationship although when focusing on a subset of ski resorts or on the geographical location of resorts, statistically significant relationships were obtained. This suggests that the natural snow conditions certainly influence the development of the snowmaking facilities although this is not the only driver and may even not be the main driver.

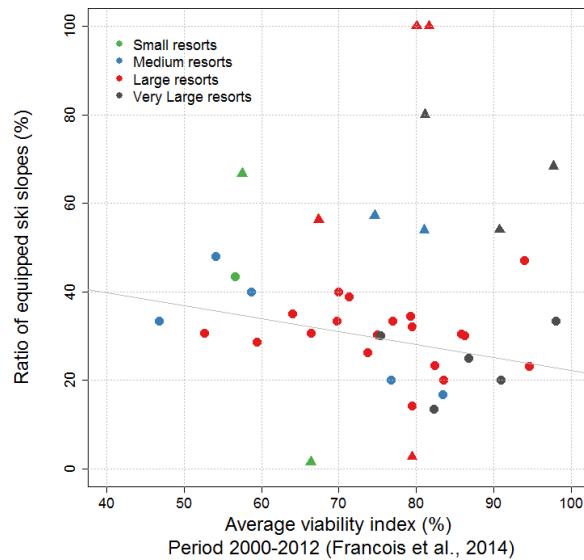


FIGURE 2.6 – Ratio of equipped ski slopes (%) versus the average viability index from François et al. (2014) for the Alpine resorts of the sample (period 2001 - 2012). The linear model (solid line) does not account for the triangular points which exceed 50% or are below 10% of equipped ski slopes with snowmaking facilities.

Water supply : a discrimination factor The average capacity of reservoirs (150 to 190 kg m^{-2}) allows to produce an equivalent MM snow depth over the total surface of ski slopes equipped with snowmaking facilities of 38 to 48 cm assuming a MM snow density of 400 kg m^{-3} (Hanzer et al., 2014), with a maximum 98 cm of MM snow depth (Section 2.4.5). Because of the low water availability and the high water demand due to a concentration in tourist overnight stays in winter (Lafaysse et al., 2011; Vanham et al., 2009), the total reservoirs volume of a given ski resort probably covers most of the total water requirements of the resort under the usual snow conditions (Vanham et al., 2007). The capacity of water reservoirs to provide the higher water demand should extend proportionally to the surface equipped with snowmaking facilities (Section 2.4.5, Table 2.3). Beyond the financial capacity to invest, this is very likely to be a major discriminating factor between ski resorts as hypothesized by Scott and McBoyle (2007). Some resorts benefit from natural lakes or hydropower facilities which already exist (Marnezy, 2008). Other ski resorts may either heavily invest in dedicated reservoirs (where technically feasible) and/or limit the size of these reservoirs (and thus the possibility to produce snow). Some resorts may even not be able to gain access to the extra volumes of water they need for technical (Pickering et al., 2010) or environmental reasons (authorizations). The location of these reservoirs (either natural, pre existing or built for snowmaking purposes) within the ski resorts has also a significant impact on the energy consumption of snowmaking facilities : the water pressure necessary for snowmaking may be provided by the elevation difference between the reservoir and the snowguns or by additional pumping systems with overproportionally higher costs of production. On the contrary to the equal access to the energy, the access to additional volumes of water and the related inequality in costs of production therefore remain highly site dependent (Scott and McBoyle, 2007; Pickering et al., 2010).

French academic holidays : key periods The answers of resorts stakeholders suggest they acknowledge the economic dependence to the French academic holidays as an external constraint (Section 2.4.4) : 50% of the seasonal overnight stays is realized within the six weeks of Christmas and winter holidays altogether in Savoie Mont-Blanc⁸ (Lecuret et al., 2014). Such importance of academic holidays had already been outlined in Eastern North America by Scott et al. (2006) or in Sweden by Falk and Hagsten (2016).

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

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

Synthesis In accordance with previous investigations of the adaptation of the ski industry to the natural variability or projected change of the climate, our survey does not reveal highly significant differences between resorts with respect to their main features (vulnerability to snow conditions, size,

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

location, etc.). The evolutions of snowmaking facilities in the French ski resorts are likely to remain highly individual (Trawöger, 2014) and in a large extent unplanned (Scott and McBoyle, 2007) and independent of the vulnerability to natural snow conditions (Hoffmann et al., 2009). However, although a deterministic approach for the development of snowmaking facilities appears irrelevant, we hypothesize that several factors strongly influence the development of snowmaking facilities both at the ski slope scale (within a ski area) and at the ski resort scale (within the ski industry).

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

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

- The larger resorts benefit from better natural snow conditions (François et al., 2014) along with longer periods of suitable conditions to produce MM snow (Spandre et al., 2015) thanks to their higher elevation. They show lower vulnerability to snow conditions (Figure 2.6) and use lower thresholds to produce MM snow (Table 2.5) with increased efficiencies (Marke et al., 2014).
- On one hand small resorts may not have the possibility to invest in such facilities or with questionable contribution to the viability of their operation (Falk, 2010; Pickering et al., 2010; Töglhofer et al., 2011). On the other hand large and very large resorts invest in extensive snowmaking facilities (Spandre et al., 2015) and turn it into a sales pitch towards customers (Morrison and Pickering, 2012) and into a proof of their awareness of the climate change challenges and of their anticipation of its impacts (Trawöger, 2014; Hopkins, 2015).
- Most of the largest French ski resorts (Paradiski, Espace Killy, Grand Massif, Serre Chevalier, Les Deux Alpes) belong to the Compagnie des Alpes (the largest ski lift operator in the world, Falk (2014)) or regional ski conglomerates e.g. Savoie Station Participation (Val Thorens) or Labellemontagne (Risoul, Espace Diamant), providing financial robustness
- The larger the ski resorts the more they are located in regions where skiing largely contributes to the local economy (Savoie, Northern Alps), which may facilitate the acceptance of means of adaptation by host communities.
- The willingness of customers to pay higher prices for ski lifts tickets (Töglhofer et al., 2011; Damm et al., 2014) due to the projected growing demand for MM snow production (Scott et al., 2003; Steiger, 2010; Pons-Pons et al., 2012) and rise of energy costs (Damm et al., 2014) is probably lower in smaller with respect to larger resorts (Riddington et al., 2000).
- An additional inequality related to the access to water supply remains within size categories of ski resorts or at the local scale.

At last, all findings on the behavioural adaptation of skiers to climate variability or projected changes showed that the demand for skiing activities is not likely to decrease proportionally to the contraction of the supply (Dawson et al., 2011; Gössling et al., 2012; Dawson and Scott, 2013; Ruttu et al., 2015) and that ski resorts where skiing will remain possible will benefit from such contraction (Scott and McBoyle, 2007; Pickering et al., 2010; Pons et al., 2014) similarly to what happened during seasons with poor snow conditions (Koenig and Abegg, 1997; Dawson and Scott, 2013; Falk, 2014). The survey therefore

highlights that the competition between ski resorts is tough and is likely to increasingly disadvantage small, low to medium altitude resorts in favour of large, high altitude resorts (Wolfsegger et al., 2008; Scott and McBoyle, 2007; Steiger, 2010; Marke et al., 2014; Pons et al., 2015)

2.5.3 Limitations to this work

This study is subject to several limitations. Firstly the sample of ski resorts may be considered as representative of medium to very large resorts (about 50% in number and ski lift power of the national total), although a complete interview of resorts stakeholders would have improved the robustness of results. However only four small resorts participated while this is the largest category (in number) with about 130 ski resorts (DSF, 2011), hampering any generalization of the results for this category. Secondly the required snow depth for skiing activities (Section 2.4.4) is limited to a single value which does not account for the steepness or roughness of the ground, which is not realistic at the slope scale where erosion or accumulation by skiers may significantly modify the need for snow depth (Fauve et al., 2002). Thirdly the usual volumes of water used for snowmaking have not been explicitly required in the survey's questionnaire which is a significant shortcoming. We therefore assumed the capacity of dedicated reservoirs may cover most of the total need for water without any data to confirm this assumption.

2.6 Conclusion and outlooks

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

In case the natural snow may not be sufficient, Medium to Very Large resorts have about 35% of their ski slopes equipped with snowmaking facilities in 2015, and almost 50% for Large and Very Large resorts by 2020 (over 30% for Medium and Small resorts). The smaller the resort the larger attention is paid to the positioning of the snowguns within the skifield (altitude, slope aspect) with a maximum altitude for the installation of snowguns significantly related to the average altitude of the ski-lifts of the resort. In most cases ski resorts have built dedicated reservoirs to supply the water for the production of machine made snow. The capacity of these reservoirs with respect to the surface of equipped ski slopes with snowmaking facilities represents an equivalent 150 to 190 liters (kg) of water per m^2 (i.e. 38 to 48 cm of machine made snow assuming a density of 400 kg m^{-3}). On one hand the ratio of equipped

ski slopes with snowmaking facilities does not show any significant relationship with the vulnerability of ski resorts to natural snow conditions although they experience contrasted conditions. On the other hand a sub sample of 34 ski resorts (by removing extreme values of the ratio of equipment) showed a significant relationship. Additionally, the analysis of resorts locations showed that the Southern Alps are the most equipped resorts at the moment (41%) and suffer a higher vulnerability to natural snow conditions (65% average viability to natural snow), at least compared to the Northern Alps (32% of equipped surface and 83% average viability), confirming that the natural snow conditions influence the level of equipment of ski resorts even though this is probably not the final decision maker but an influential factor among many others.

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

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

Appendix of chapter 2 : questionnaire

The ski resort

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

Snowmaking practices

- Is the resort equipped with snowmaking facilities ?
- If not, do you plan to get equipped ? When ?
- The total ski slopes surface equipped with snowmaking facilities ?
- Please detail the number of air/water guns in your resort ? Of fan guns ?
- Is the priority given to low altitude ski slopes for the installation of snowmaking facilities ? If yes, please detail the altitude
- Is the priority given to ski slopes with a specific aspect for the installation of snowmaking facilities ? If yes, please detail the aspect
- Do you plan to extend the ski slopes surface equipped with snowmaking facilities ?
- If yes, please detail the extra surface equipped and the year when completed ?
- Among the following which water supply is used in your resort for snowmaking purposes ?
 - Water reservoirs. If yes, please detail the reservoirs total capacity
 - Waterways or natural lakes
 - Drinking water supply
 - Hydroelectric dam
 - Other. Please detail
- When is the snowmaking installation ready to produce machine made snow ?
 - Before the 15th of October
 - Between the 15th of October and the 1st of November
 - Between the 1st of November and the 15th of November
 - After the 15th of November
- Which wet-bulb temperature threshold do you usually use to trigger snowmaking ? - 3°C, - 4°C,

- 5°C or Other? Please detail
- Do you record the water volumes used for snowmaking purposes?
- Do you intend to reduce the costs related to snowmaking?
- If yes, do you plan to optimize the amount of production? To optimize the process (investments in more efficient facilities, personnel reduction, etc.)?
- What is the main limit to the production of machine made snow in your resort?
 - The water supply
 - The energy costs
 - I stop when i do not need to produce more snow
- Once produced, do you let the machine made snow rest before grooming it? If yes, please detail how long
- Comments

Grooming practices

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

Other practices

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

Chapitre 3

Snowmaking in the French Alps. Climatic context, existing facilities and outlooks

This chapter corresponds to the paper by Pierre Spandre, Hugues François, Samuel Morin et Emmanuelle George-Marcelpoil, "Snowmaking in the French Alps. Climatic context, existing facilities and outlooks", *Journal of Alpine Research*, 103-2 — 2015. doi : 10.4000/rga.2913

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3.1 Introduction

Winter tourism is now both a major attraction in the French Alps and a leader of mountains local economy. During the 1970s, “ex-nihilo” resorts were built from scratch in altitude lands of French mountain regions to allow the access to skiing activities to the widest possible range of people. These resorts integrate all services tourists may need during their stay from the accommodation to entertaining activities. That new type of ski resorts attracted an increasing number of tourists and the economical revenue generated by these altitude resorts soon exceeded the declining revenue from industries down in the valleys (Francois and George-Marcelpoil, 2012). In 2013, winter tourism generated 7 billion euros and employed 120 000 people (DSF, 2014). Ski lifts operators bear the leadership of that market by ensuring the access to the main activity (skiing), the safety and the comfort of skiers (Guily, 1991). For the first time in the late 1980s, that market encountered economical losses (Lorit (1991) and Pascal (1993)) because of several successive winters with little natural snow (Durand et al., 2009b). Snowmaking appeared as the best option to mitigate the meteorological annual variability and climate change effects on snow conditions (Steiger and Mayer, 2008) and spread in the French Alps until 20% of ski tracks surface got covered by snowmaking facilities in 2009 (ODIT, 2009). While snowmaking first appeared as a sign of weakness, both skiers and ski lifts operators now consider it as a guarantee of snow for a successful stay (for skiers) and a sufficient revenue (for ski lifts operators, Paccard (2011)). Snowmaking is now the main topic of many discussions, such as the economical balance between the guarantee of snow and the pressure due to extra investments, the natural risks related to mountain works (e.g. artificial lakes, Evette et al. (2011b)), or even environmental issues (e.g. water resource management, Magnier (2013)). All alpine countries now produce snow. Hahn (2004) collected existing data and estimated that about 40% of Italian and Austrian ski tracks were equipped with snowmaking facilities in 2004 against 10% only of Swiss and German ski tracks. In the meantime, Agrawala et al. (2007) showed that no systematic method had ever been used and that the calculation of the ratio of equipped ski tracks may differ from a country to another. The French agency for tourism activities observation ODIT France (standing for “agence d’Observation, de Développement et d’Ingénierie Touristique française”) did not publish any detailed method either (Paccard, 2011). ODIT latest estimations of snowmaking facilities were published in 2009 and are still a reference for professionals (Badré et al., 2009) while these facilities are constantly evolving. In order to update these data, we develop here the strongest possible method to assess the current and upcoming level of equipment with snowmaking facilities of French Alps resorts, splitted into distinct categories. In a first section we describe a specific database which we will use to describe ski resorts through structural data (Marcelpoil et al., 2012). In a second section, a survey we organised in 2014 to investigate ski resorts snowmaking facilities and practices is described and its results are displayed. We investigate in a third section the climatic context of snowmaking by assessing how much time was available to produce snow in the French Alps over the last 50 years regarding the altitude and geographical areas. Last, we discuss a few points of that work in a fourth section. Our goal is to provide here an updated and reliable information of current facilities in the French Alps which takes part into a project of analysis and simulation of snow conditions in ski resorts by crossing socio-economic and physically based models (François et al., 2014).

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

TABLE 3.1 – Ski resorts categories regarding the ski lift power

3.2 The survey's sample and structural data on ski resorts

3.2.1 Professionals survey

In order to figure out the current and coming levels of equipment with snowmaking facilities, we set up an online survey towards professionals. The national association of ski patrol managers (ADSP, standing for "Association Nationale des Directeurs de Pistes et de la Sécurité des stations de Sport d'Hiver") provided 161 contacts. All these contacts manage technical services (grooming, snowmaking) in ski resorts in all French mountain regions. A code was dedicated to every contact to guarantee a personal access to the survey as well as the confidentiality of data.

3.2.2 The socio economic database "BD Stations"

We used the data from the socio-economic database "BD Stations" to assess the representation of the survey's sample among all French Alps resorts and to treat and extrapolate the survey's results. The database BD Stations was created on request of the "Comité de Massif Alpes" committee, a governing institution set up after the "Loi Montagne" law was voted in 1985. The BD Stations goal is to give access to a wide range of data and sources focused on ski resorts through a structured frame. These data cover administrative aspects (ski lifts are part of public services and under the responsibility of municipalities) as well as economical aspects (the resort's management can be handled by the municipality or transferred to semi-public or private companies). The BD Stations is a powerful tool to support investigations focused on large territories where winter sports are an activity among many others or zoomed at the scale of a single ski-lift. Specific rules are applied to ski lifts which installation and operation are thus supervised by a national service (STRMTG, standing for "Services Techniques de Remontées Mécaniques et Transports Guidés"). The STRMTG administrates a dedicated database to ski lifts (CAIRN, "CATalogue Informatisé des Remontées Mécaniques Nationales") which includes technical characteristics of each ski lift such as the Ski Lift Power.

The Ski Lift Power (SLP) is an indicator of the size of a ski lift, commonly employed by the French national association of ski resorts (DSF, standing for "Domaines Skiables de France"). The SLP is defined as the product of the elevation difference between the bottom and the top of a ski lift (in km) and its flow of persons per hour (pers h⁻¹), thus expressed in (pers km h⁻¹, DSF (2014)). Aggregated for each ski resort, it allows to classify them in four resorts types as described in Table 6.1, according to François et al. (2014). These data are completed with geographical information from the database BDTOPO (25 m of resolution) developed by the French Geographical Institute (IGN, "Institut Géographique National"). The geographical location of ski lifts can be used to infer an estimate of resorts ski slopes which was already used for research purposes (François et al., 2014). We refer here to the representation of ski slopes named "gravitational envelopes" (François et al., 2016).

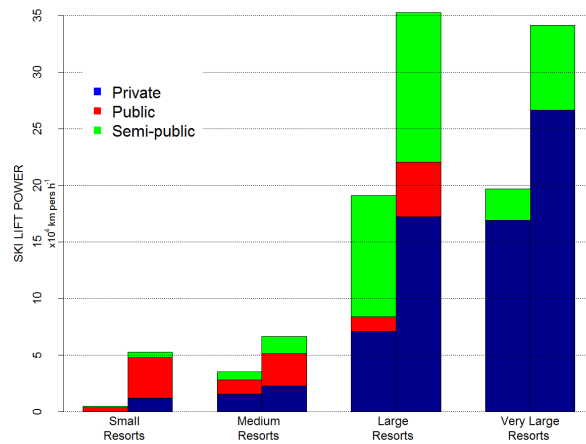


FIGURE 3.1 – Ski lift power and management mode of survey's sample resorts (left) and all French Alps resorts (right), by category

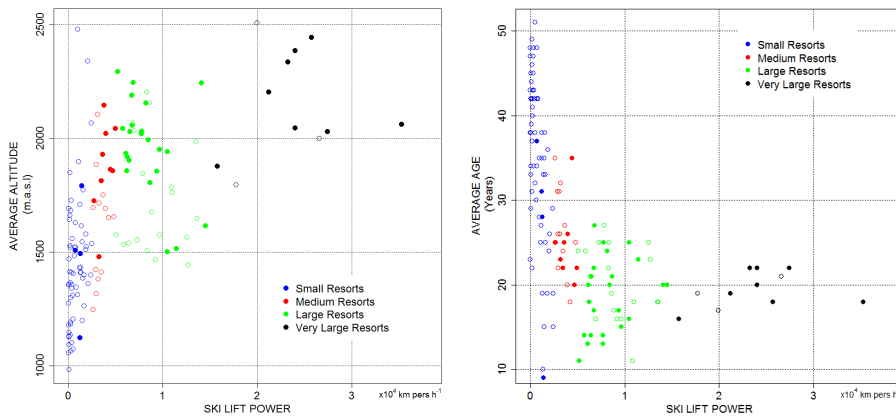


FIGURE 3.2 – a. Ski lifts Average Altitude (left) and b. Average Age (right) of survey's sample resorts (●) and other French Alps resorts (○)

3.2.3 Representation

We presented our approach on the 7th of October 2014, during the ADSP annual assembly in Montpellier. On that day, paper versions of the survey were collected (18 distinct resorts) from attendants of the assembly. At last, 56 resorts took part in the survey when we closed the online access on the 9th of January 2015. Among them were 44 French Alps resorts which we will consider in this work, consistently with the BD Stations (so far data are available over the French Alps only). Excepted from Small resorts, the resorts from the survey's sample cover from 45 to 60% of the whole French Alps resorts for each category, both in terms of SLP and of number (Annexe 3.9 and 3.1). Overall, the sample of resorts covers 53.2% of the total French Alps SLP.

Figures 3.1 and 3.2 illustrate that the dispersion within each category of the sample is consistent in terms of management mode, average altitude and age of the ski lifts with the dispersion of resorts within that category of the whole French Alps resorts. Consequently, we assumed that each category of the sample can be considered as representative of the French Alps category of resorts, excepted from S resorts which we will consider specifically. We did not take into account the survey's results

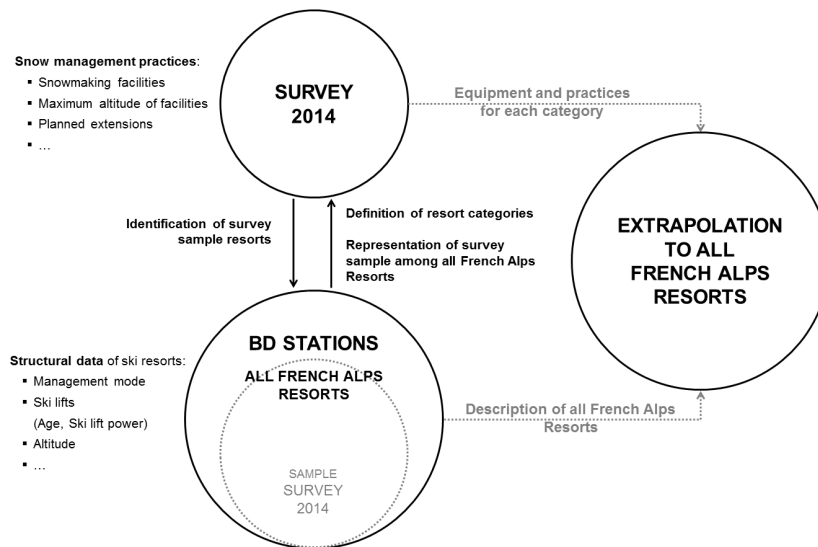


FIGURE 3.3 – Schematic treatment of survey’s results thanks to data from “BD Stations” database

from the sample of S resorts since it did not appear representative of the French Alps population of S resorts. Instead we treated the S category thanks to three assumptions based on the survey’s results of the M category. Since the SLP of the S category is only 7% of the total SLP of French Alps resorts (Annexe 3.9), the misjudgement we may commit over the general results appears very limited. The three assumptions we used are based on Francois et al. (2016) who showed that the ratio of the gravitational envelope (i.e. all slopes that can be accessed from a resort’s ski lifts) to the SLP of a resort decreases with the resort size. That ratio is twice higher for S resorts compared to M resorts (0.42 vs. 0.21 ha (km pers $h^{-1})^{-1}$). In the meantime, the ratio of ski tracks surface to the gravitational envelopes surface is steady among categories (about 10%, Francois et al. (2016) and ODIT (2009)). As a result, our first assumption is to consider that the ratio of ski tracks surface to the SLP is twice higher for S category than for M category. Secondly we assumed that the level of equipment with snowmaking facilities is more related to ski lifts facilities (and thus the SLP) than it is to the ski tracks surface. Consequently, the ratio of the equipped surface with snowmaking facilities to the SLP of the S category is the same than the ratio of the M category. Last, our third assumption is that the ratio of extra surface equipped with snowmaking facilities by 2020 to the SLP is twice lower for the S category than the ratio of M category. That third assumption is mostly based on the clear distinction between M , L and XL categories in terms of extensions plans (Table 3.2 and Annexe 3.10).

3.3 Treatment and extrapolation of survey’s results

All resorts of a category are identified within the BD Stations which allows to aggregate their results to provide an integrated result and the SLP of the sample for that category. The BD Stations also provides the total SLP of French Alps resorts for each category. The ratio of the SLP of the sample to the SLP of the total French Alps resorts is used to extrapolate the sample’s results, for each category (Figure 3.3 and Annexe 3.10). In order to assess the uncertainty of our results, we considered two different scenarios of higher and lower equipment by removing the first or last quartile of the survey’s

Resorts categories	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? Replied Yes	100% (4/4)	100% (8/8)	42% (10/24)	25% (2/8)	55% (24/44)
Do you plan to extend your snowmaking facilities? Replied Yes	50% (2/4)	63% (5/8)	88% (21/24)	100% (8/8)	82% (36/44)
When should this be completed (Average)	2018 (± 2 years)	2020 (± 3 years)	2019 (± 4 years)	2021 (± 3 years)	2020 (± 3 years)

TABLE 3.2 – Planned extensions and relation to altitude of snowmaking facilities

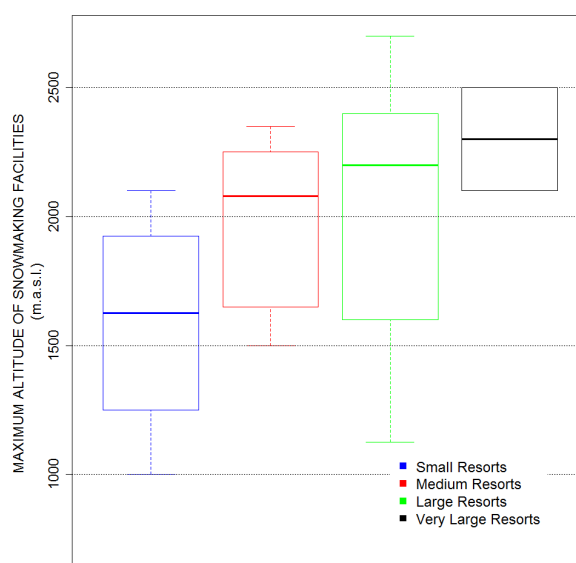


FIGURE 3.4 – Maximum altitude of snowmaking facilities. These results are limited to resorts who declared they give priority to lower altitude areas to install snowmaking facilities (Table 3.2). The median is shown in bold, the box includes the second and the third quartile while whiskers correspond to extreme values, for each category.

sample when resorts are ranked by their level of equipment with snowmaking facilities. This is equivalent to assume that the alpine population is as equipped as the 3 most equipped resorts of the sample out of 4 (Higher equipment assumption) or on the contrary that the alpine population is as equipped as the 3 less equipped resorts of the sample out of 4 (Lower equipment assumption). We also assumed that the ratio of the ski tracks surface to the SLP would remain steady until 2020.

3.3.1 Survey's results : facilities extensions and relation to altitude

According to survey's results, the facilities extensions and relations to the altitude highly depend on the category (Table 3.2 and Figure 3.4). The larger the resort the less priority is given to low altitude areas to install snowmaking facilities while the more the resorts plan to extend these facilities.

3.3.2 Survey's results : estimating the ratio of equipped surface

All results are shown in Annexe 3.10. Figure 3.5 also displays the extrapolated ratio of equipped surface with snowmaking facilities according to the sample results and both the higher and lower

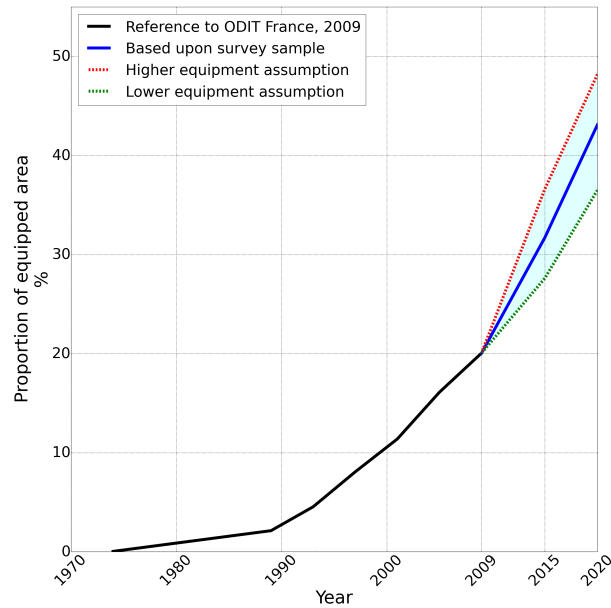


FIGURE 3.5 – Evolution of the ratio of ski tracks equipped surface with snowmaking facilities in the French Alps from 1970 and outlooks for 2020.

equipment assumptions. The surface of ski tracks was extrapolated for each category according to previous sections (Figure 3.3 and Annexe 3.10). Aggregated over the French Alps, we got a total surface of ski tracks of 16 500 ha which is lower than the values from ODIT (2009), ranging from 19 000 to 22 500 ha. Unfortunately, the methods employed by ODIT (2009) are not known (Paccard, 2011). According to the survey’s results, the ratio of equipped surface with snowmaking facilities is 32% today. The M, L and XL resorts are similarly equipped : about 35% of their ski tracks surface. However in the next few years, they do not plan to extend their facilities by the same rate. The XL resorts should extend the existing surface equipped with snowmaking facilities by 46% within 5 years, while L resorts plan a 37% increase of that surface and the M resorts an 18% increase. The overall surface equipped with snowmaking facilities should reach 43% of the total ski tracks surface in The French Alps in 2020. As far as we know, no investigation of meteorological conditions suitable for snowmaking has been produced while these investments in snowmaking facilities were decided. While the need for suitable conditions grows with snowmaking facilities, we had no idea of how important the potential for snow production is and thus how close to the availability of suitable conditions the resorts get by increasing their facilities. This is the goal of the third section.

3.4 Past evolution of climatic conditions suitable for snowmaking

3.4.1 Meteorological data

The meteorological system SAFRAN (standing for “Système d’Analyse Fournissant des Renseignements Atmosphériques à la Neige”) provides meteorological data (temperature, precipitations, etc.) for mountain areas of an approximate 1000 km² surface referred to as “massif” (Figure 3.6). Within each massif, the meteorological conditions are supposed to be homogeneous and to depend only on the altitude (Durand et al., 1993). The altitudinal step is 300 m and the time resolution is 1 h. SAFRAN

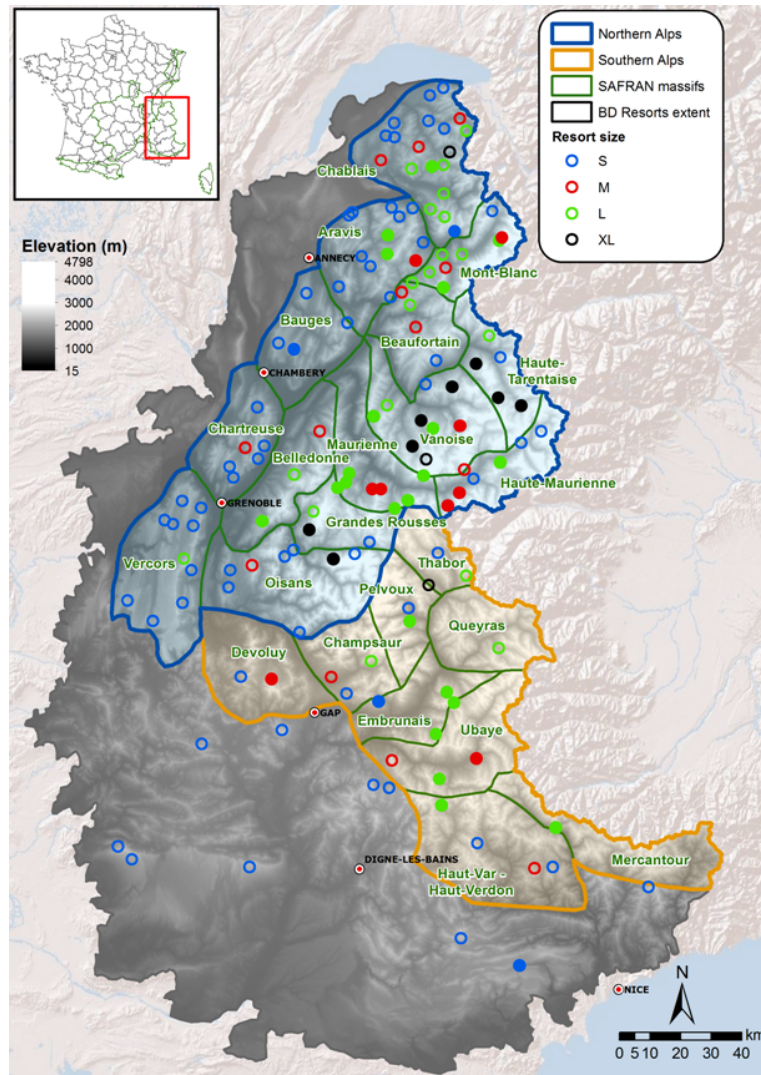


FIGURE 3.6 – Geographical areas covered by this work, by grouping SAFRAN massifs : Northern Alps, Southern Alps and all French Alps. The survey’s sample resorts (●) and other French Alps resorts (○) are also shown by category

merges numerical weather predictions model outputs (large scale atmospheric variables), surface observations (automatic weather stations, manual observations) and radiosonde observations. That data assimilation scheme provides information at an hourly basis for the last 54 years (Durand et al., 2009b). However, SAFRAN is based on large scale models reanalysis and observations which evolved from their creation, particularly from the 1980s which is a source of variability in time and space (Vidal et al., 2010). Despite these uncertainties, SAFRAN is a powerful tool for research purposes that has been extensively used to assess climate change impacts in French mountain regions (Durand et al., 2009b; Lafaysse et al., 2011; Durand et al., 2009a).

3.4.2 Definition of the snowmaking potential and situations covered by this work

Snowmaking highly depends on meteorological conditions (air temperature and humidity, wind). The main variable used by professional snowmakers and snowguns 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 results displayed and discussed in that work are based on T_w which we calculated from the air temperature and relative humidity provided by SAFRAN, thanks to (Jensen et al., 1990) method. Given the current technology, snow can be produced below the wet-bulb temperature threshold of -2°C (Olefs et al., 2010) even though the efficiency is limited until a threshold of -5°C (Marke et al., 2014). We considered here the suitable periods for snowmaking that last at least four hours (consistently with professionals practices) and during which the wet-bulb temperature is below the specified threshold. The snowmaking potential is defined as the summed duration of all periods that are suitable for snowmaking. Three geographical areas have been chosen by grouping SAFRAN massifs (Figure 3.6) : the Northern Alps (14 massifs), the Southern Alps (9 massifs) and all the French Alps (23 massifs). We also chose four altitude levels : 1200 m.a.s.l, 1500 m.a.s.l, 1800 m.a.s.l, 2100 m.a.s.l. These altitudes cover the usual altitudes of resorts villages and of slopes equipped with snowmaking facilities (Table 3.2) while they also present the most uncertainties due to the lack of snow. In terms of wet-bulb temperature threshold, we chose -2°C (as the technical limit) and -5°C (as the "higher efficiency" limit). Last, we calculated the snowmaking potential for two distinct periods : the autumn (1st of October - 1st of January) and the whole winter season (1st of October - 1st of April). The autumn is the period when the production is the most important in ski resorts (Hanzer et al., 2014), thus any change of suitable conditions during that period would have an important effect on snowmaking practices. Anyway, snowmaking occurs during the whole season, so we decided to take both periods into account. The combination of all these factors provides 48 distinct cases which we treated over the (1961-2014) period. That way, we aim to describe the current situation and the past evolution from 1961 of the meteorological potential for snow production.

3.4.3 Assessing trends

The analysis of SAFRAN data provides for each massif a potential for snow production which we simply averaged to get a snowmaking potential for the three geographical areas : Northern Alps, Southern Alps and all French Alps. That method was applied for each year and altitude (Figure 3.7). We calculated the growth rate and the correlation of the linear trend of the average curve with time as well as the standard deviation of the average curve (to assess its variability) and the average snowmaking potential for the (1961-1970) and (2005-2014) decades. The significance level of the trend was determined thanks to a statistical approach based on Monte-Carlo methods (Chène and Savès, 2008). That approach was 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 serie of the same values with time in at least 95% of draws.

3.4.4 Results : past evolution of snowmaking potential

According to our analysis of SAFRAN data, the stronger the trend (i.e. the higher the magnitude of the growth rate) the higher the significance level. All twelve significant cases have negative growth rate meaning their snowmaking potential decreases from 1961. As an example for all the French Alps at an altitude of 1200 m.a.s.l, the season snowmaking potential (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 : the snowmaking potential decreases by 6 to 8 h/year, see Figure 3.7. The snowmaking potential in autumn does not present any significant trend during the (1961-2014) period (only two significant cases out of 24) while the season snowmaking potential presents many significant cases. The ratio of the potential

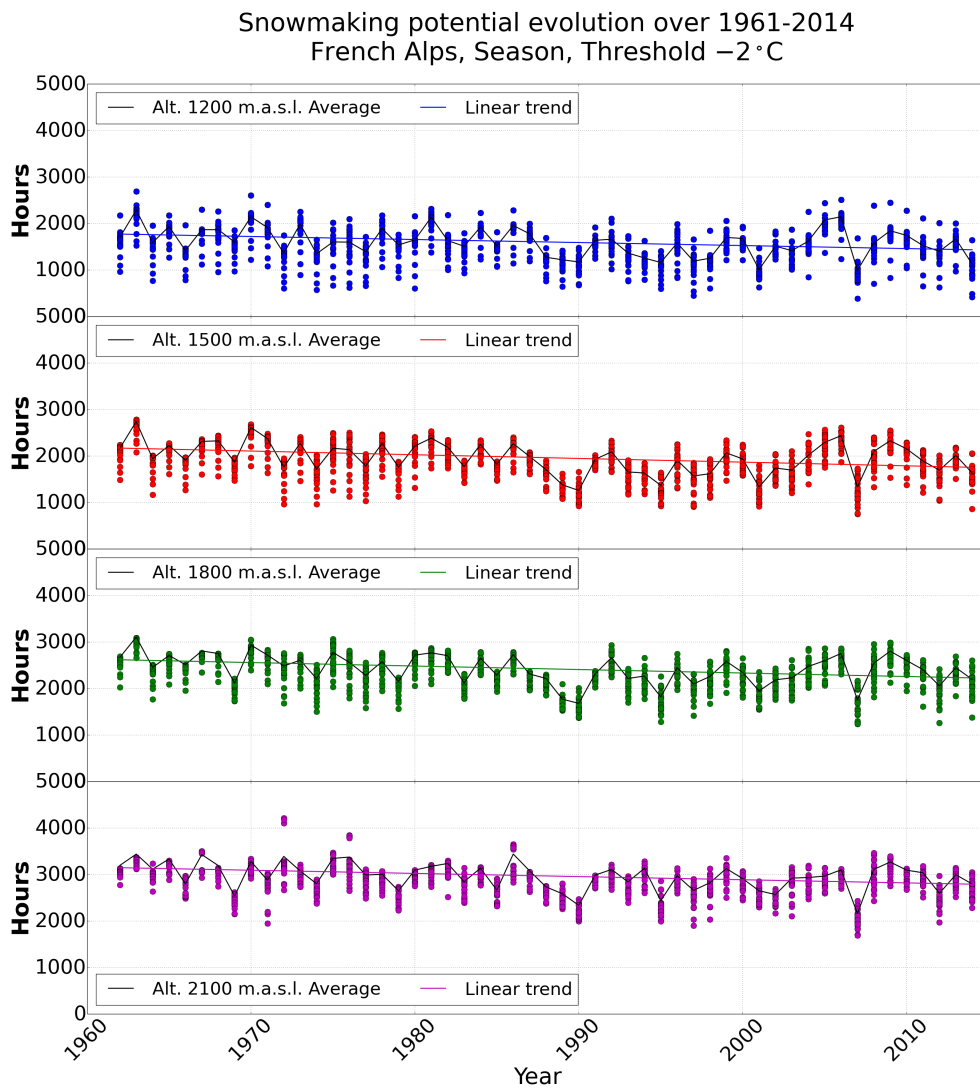


FIGURE 3.7 – Snowmaking potential for the French Alps on the (1961-2014) period. Here is shown the potential over the whole season, with a threshold of wet-bulb temperature of -2°C . Each point is a SAFRAN massif, the black curve is the average of all massifs and the coloured curve is the linear trend of that average curve.

in autumn to the potential in the whole season was 35% (for a threshold of -2°C) in (1961-1970) while it was 37% (-2°C) to 34% (-5°C) in (2005-2014). 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 higher 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 even get confirmed for all the French Alps for a threshold of -2°C , even though the trends in the Southern Alps are not significant for the altitudes from 1200 to 1800 m.a.s.l. All results can be found in Annexe 3.8. Even though no publication investigated the evolution of snow production periods under changed climate conditions in the coming decades, all results prove that the trends we noticed here should be confirmed or even enhanced in the future since they always suggest an increase of the air temperature at all altitudes, no matters the scenario (Lafaysse et al., 2014) and (Castebrunet et al., 2014)).

3.5 Discussion

3.5.1 Variability and significance

The important variability of the snowmaking potential is due to meteorological conditions variability both in space and time. First, we grouped several SAFRAN massifs which climatic influences may differ and thus create some spatial variability. On top of that, the annual variability of meteorological conditions is well-known by mountain professional and may be very important (Durand et al., 2009a). According to our analysis, the lower the snowmaking potential, the higher the relative variability (Annexe 3.8). As an example the average snowmaking potential (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 1800h 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 may be “hidden” by the variability of the signal. This is particularly true for the autumn period and low altitudes cases. However, the ratio of the potential in autumn to the potential during the whole season is more important for the (2005-2014) period (34 to 37%) than it was for the (1961-1970) period (32 to 35%). That may confirm that the potential in autumn did actually not decrease as much as the season potential did.

3.5.2 What margins of extensions ?

In 2009, 19 millions of m^3 of water were used to produce snow on the 5300 ha of equipped ski tracks i.e. 0.358m^3 per m^2 of ski track (Badré et al., 2009). Since three snowguns are installed per ha of equipped ski tracks (national average, Badré et al. (2009)), every snowgun throws 1192m^3 of water a season. Using a usual flow of $8\text{m}^3\text{h}^{-1}$ of water, the needed time is 149 h per snowgun per year. That value may appear very low compared to snowmaking potentials (Annexe 3.8) but one should pay attention that the gap is certainly not that important. First, production constraints are not limited to the wet-bulb temperature, the wind or the water availability also shrink that potential. On top of that all snowmaking facilities of a resort can not be used at the same time (air and water pumping can usually not feed all snowguns in the meantime). Thus for a resort which may be able to have the third of its snowguns working at the same time, 450h 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 and -2°C and thus with lower efficiency (Marke et al., 2014).

3.6 Conclusion

In order to describe the current and upcoming situations of snowmaking facilities in the French Alps, we described here the results of a survey we organised in 2014 thanks to a list of contacts from the French national association of ski patrol managers. Consistently with the “BD Stations” database, we limited that work to alpine resorts. It might be extended to other French mountain regions that are already covered by the meteorological system SAFRAN but not by the BD Stations yet. Our survey showed that 32% of ski tracks surface are now equipped with snowmaking facilities. That ratio increased very quickly from the 1990s and should reach 40% of equipped ski tracks in 2020. Even though the Medium to Very Large resorts are now equipped at similar levels, their plans to extend their snowmaking facilities highly depend on their size. The Very Large resorts should be the most equipped resorts in 2020 (about 50% of their ski tracks surface), followed by the Large (41%) and the Medium resorts (41%). Our survey’s results show the inequalities between resorts facing the annual variability of snow conditions and the climate change effects. The Very Large resorts already benefit from better natural snow conditions thanks to their higher altitude (François et al., 2014) which also means more important climatic margins to extend their snowmaking facilities (the higher the altitude, the higher the snowmaking potential). Since they plan the largest extensions (+46% of equipped ski tracks between 2015 and 2020), the Very Large resorts also prove they have the most important means to invest in new facilities and thus mitigate the uncertainties of snow conditions due to the meteorological annual variability and the climate change (Castebrunet et al., 2014). Snowmaking is now thought as the best strategy against climate change effects (Steiger and Mayer, 2008) but that strategy might fail. Snow production may compensate the lack of natural snow if several conditions are respected which might not be the case if for example the early winter season shows dry and warm meteorological conditions (such as 2006-2007, François et al. (2014), (Spandre et al., 2014)). Our work shows that snowmaking potentials in the French Alps are limited and tend to decline from 1961 while snowmaking facilities still increase. If the trends we observed get confirmed in the future, there will probably be a time when the need for water resources and suitable meteorological conditions for snowmaking will match their availability. All resorts are not equally impacted but all will have to face increasing costs since they will have to produce snow in more marginal conditions, with lower efficiency (Marke et al., 2014). The gain of productivity thanks to snowmaking should be balanced with the investment and cost damping of such an installation, given the meteorological potential to produce snow. The interest of developing snowmaking facilities is limited to resorts which balance could be positive. Since most resorts are apparently increasing their snowmaking facilities, we may wonder whether they will actually benefit from these investments in coming decades.

Appendix of chapter 3 : exhaustive results of snowmaking potential and facilities

- Alt. is the altitude (m.a.s.l)
- $\alpha_{1961-2014}$: Growth rate of the snowmaking potential linear trend (hours/year)
- $D_{1961-70}$: Average snowmaking potential over the (1961-1970) period (hours)
- $D_{2005-14}$: Average snowmaking potential over the (2005-2014) period (hours)
- $\sigma_{1961-1970}$: Standard deviation of the snowmaking potential over the (1961-2014) period
- r : Correlation coefficient of snowmaking potential curve with time

How to read that table? (red circled cells) : The snowmaking potential in Autumn in the Northern Alps at an altitude of 1200 m.a.s.l is described for a wet-bulb temperature threshold of -2°C :

- It decreases at a rate of 4 hours/year
- Its average was 650h over the (1961-1970) period
- Its average was 557h over the (2005-2014) period
- Its variability in time and space is ± 43 h on average
- The correlation of its linear trend with time is 0,30
- Its significance score is 97%

All situations with a significance score of 95% or more are printed in green.

			Alt. (m.a.s.l.)	$\alpha_{1961-2014}$ (h/year)	$D_{1961-70}$ (h)	$D_{2005-2014}$ (h)	$\sigma_{1961-2014}$ (h)	r	Significance Score (%)
AUTUMN (October the 1st – January the 1st)	-2°C	Southern Alps	1200	0	549	556	99	0,04	21
			1500	0	684	672	123	0,03	17
			1800	0	825	785	129	0,03	16
			2100	-1	1012	956	138	0,10	55
		Northern Alps	1200	-4	650	557	43	0,30	97
			1500	-4	777	699	48	0,27	95
			1800	-2	904	880	53	0,17	77
			2100	-3	1116	1046	73	0,21	87
		All French Alps	1200	-2	644	592	72	0,21	86
			1500	-2	775	723	77	0,18	81
			1800	-2	913	883	81	0,11	58
			2100	-3	1121	1055	94	0,18	80
	-5°C	Southern Alps	1200	0	239	244	64	0,03	16
			1500	1	289	323	81	0,10	54
			1800	1	393	403	97	0,09	45
			2100	0	579	550	98	0,03	16
		Northern Alps	1200	-2	308	235	27	0,24	92
			1500	-1	369	347	30	0,13	65
			1800	-1	487	482	37	0,06	33
			2100	-1	673	649	42	0,05	29
		All French Alps	1200	-1	297	256	44	0,13	66
			1500	0	353	355	49	0,04	24
			1800	0	471	473	58	0,00	2
			2100	0	665	638	61	0,02	12
SEASON (October the 1st – April the 1st)	-2°C	Southern Alps	1200	-2	1601	1507	214	0,11	55
			1500	-3	1992	1847	265	0,14	68
			1800	-4	2441	2192	242	0,23	90
			2100	-6	2921	2654	215	0,37	99
		Northern Alps	1200	-9	1815	1516	94	0,44	100
			1500	-11	2247	1918	94	0,48	100
			1800	-9	2636	2378	99	0,43	100
			2100	-7	3025	2867	109	0,34	99
		All French Alps	1200	-6	1828	1606	163	0,33	98
			1500	-8	2244	1984	163	0,36	99
			1800	-8	2674	2413	164	0,37	99
			2100	-7	3116	2909	168	0,36	99
	-5°C	Southern Alps	1200	0	757	712	139	0,00	0
			1500	1	947	953	195	0,07	36
			1800	0	1276	1205	230	0,02	10
			2100	-2	1749	1614	223	0,09	47
		Northern Alps	1200	-5	926	716	63	0,29	97
			1500	-5	1165	1017	73	0,25	92
			1800	-4	1512	1393	85	0,20	84
			2100	-4	1956	1851	89	0,18	81
		All French Alps	1200	-3	910	767	104	0,17	80
			1500	-2	1129	1045	119	0,13	63
			1800	-2	1485	1384	137	0,11	59
			2100	-3	1959	1839	137	0,15	71

FIGURE 3.8 – Evolution of the snowmaking potential over the (1961-2014) period

	Small Resorts (S)	Medium Resorts (M)	Large Resorts (L)	Very Large Resorts (XL)	All Resorts
Number of resorts in the survey's sample N_{Survey}	4	8	24	8	44
Ski Lift Power of survey's sample resorts (km pers h ⁻¹) SLP_{Survey}	4700	29400	196900	197900	428900
Number of French Alps Resorts N_{Alps}	67	17	42	14	140
Ski Lift Power of all French Alps Resorts (km pers h ⁻¹) SLP_{Alps}	55000	58300	351200	341600	806200
Ratio (% of Number) $\frac{N_{Survey}}{N_{Alps}}$	6,0	47,1	57,1	57,1	31,4
Ratio (% of SLP) $\frac{SLP_{Survey}}{SLP_{Alps}}$	8,5	50,5	56,1	57,9	53,2

FIGURE 3.9 – Survey's sample resorts for each category

			Small Resorts (S)	Medium Resorts (M)	Large Resorts (L)	Very Large Resorts (XL)	All Resorts
BASE : Survey's sample	2015	Ski slopes surface (ha)	2556	1354	6928	5644	16482
		Equipped surface (ha)	449	476	2396	1899	5219
		Ratio of equipped surface (%)	18	35	35	34	32
	In 2020	Equipped surface (ha)	488	559	3288	2775	7110
		Growth rate	+ 9%	+ 18%	+ 37%	+ 46%	+ 36%
		Ratio of equipped surface (%)	19	41	48	49	43
Lower equipment assumption	2015	Equipped surface (ha)	401	424	1679	2045	4549
		Ratio of equipped surface (%)	15	30	28	28	28
	In 2020	Equipped surface (ha)	433	494	2282	2811	6019
		Ratio of equipped surface (%)	16	35	38	38	37
Higher equipment assumption	2015	Equipped surface (ha)	540	572	2761	2159	6031
		Ratio of equipped surface (%)	20	40	39	40	37
	In 2020	Equipped surface (ha)	573	642	3769	2956	7940
		Ratio of equipped surface (%)	21	44	53	55	48

FIGURE 3.10 – Ski tracks surfaces equipped with snowmaking facilities in the French Alps. Current facilities and outlooks

Deuxième partie

Observations and modelling of snow properties on ski slopes

Chapitre 4

Integration of snow management in a detailed snowpack model and evaluation through seasonal observations

This chapter corresponds to the paper by Pierre Spandre, Samuel Morin, Matthieu Lafaysse, Yves Lejeune, Hugues François et Emmanuelle George-Marcelpoil, "Integration of snow management into a detailed snowpack model", *Cold Region Sciences and Technologies*, Published January 15th 2016. DOI : 10.1016/j.coldregions.2016.01.002

The section 4.7 is a complementary material to the above paper we realized during winter 2015 - 2016 and analyzed with the help of Martin Lejeune, a master student from Polytech Chambéry (Université Savoie Mont Blanc) under my supervision from May to July 2016.

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4.1 Introduction

The management of snow on ski slopes is a key socio-economic and environmental issue in mountain regions. Indeed, the winter sports industry has become a very competitive global market (Agrawala et al., 2007). Ski lift operators face multiple expectations from both consumers and investors (Fauve et al., 2002; DSF, 2014) such as ensuring opening/closing dates and maintaining safe and homogeneous conditions, etc. Further to operating costs (Damm et al., 2014), the increasing attention paid to environmental issues (Steiger, 2010; Magnier, 2013) arouses the interest of both policy makers and ski lift operators concerning optimization levers of energy and water consumption and for reliable data concerning the ability of the snow industry to face climate challenges (Scott and McBoyle, 2007).

Several methods such as snow grooming are employed by ski resort operators to provide comfortable skiing conditions, to protect snow from natural and human-induced ablation processes, or to compensate for snow deficits by means of snowmaking (Guily, 1991; Fauve et al., 2002). Snow management processes (grooming and snowmaking in particular) induce significant changes in the physical state and behaviour of the snowpack so that snow on ski slopes is markedly different from natural snow conditions in their surroundings (Fahey et al., 1999; Rixen et al., 2001). Indeed, be it fully natural or under the influence of human interference, snow cover constantly undergoes physical transformations which occur under the influence of atmospheric conditions (Armstrong and Brun, 2008) and due to the intrinsic physical properties of snow layers. These in turn influence the surface energy budget and the evolution of internal properties (Brun et al., 1992; Vionnet et al., 2012). An assessment of the snow conditions in ski resorts therefore requires a method which handles simultaneously physical processes occurring in snow and the impact of snow management practices. This is because the reaction of the snowpack to all of its drivers is strongly non-linear and is affected by several thresholds.

However, investigations of the vulnerability of the ski industry have often been based on natural snow conditions and employed empirical rules (Crowe et al., 1973; Durand et al., 2009b). Since the early 2000s, several studies have initiated accounting for snow management practices in assessments of snow conditions in ski resorts. Rixen et al. (2011) for example, computed potential snowmaking days based on climate projections of air temperature and humidity. These computations took place on several study sites in Switzerland without further analysis of snow conditions. This was due to the lack of a snowpack model able to process the information in question. Scott et al. (2003) implemented snowmaking operational rules in a simple snowpack model (degree-day approach). This was in order to assess the impact of climate change on ski season duration using various snowmaking technologies represented by different model configurations. However, this study does not account for the fact that the physical properties of machine-made snow (MM snow; Fierz et al. (2009)) differ from natural snow, and it would not be possible with the model to handle this information. Explicitly accounting for snow management techniques in snowpack models is something that has already been developed in a few cases. For example, Keller et al. (2004) used field observations of snow depth on groomed slopes to determine the compaction rate on a groomed ski slope. While this method may be informative in terms of processes occurring during the course of a simulated snow season, it depends on the weather conditions during this specific season and on local measurements. This hampers utilization on a large scale. Climate projection or the testing of various snow management policies are even more affected. Interdisciplinary programs recently combined physical snowpack models with detailed human approaches of snow management (Howard and Stull, 2014; Hanzer et al., 2014).

Nevertheless, the effects of snow management on snowpack properties are still rarely described in literature and only a few studies have reported detailed field observations (Keddy, 1979; Guily,

1991; Keller et al., 2004; Howard and Stull, 2014). In order to build a tool capable of addressing snow conditions on ski slopes for a wide range of resorts we have explicitly integrated comprehensive grooming and snowmaking approaches into the detailed multi-layer snowpack model Crocus (Vionnet et al., 2012). Grooming and snowmaking were implemented in Crocus based on our physical comprehension of processes, literature and interviews with professionals. The latter were involved in our development strategy to represent their management practices in the most consistent way, which is critical for any further use of such a model. The model was evaluated with field measurements (depth, snow water equivalent and vertical profiles) carried out in four resorts in the French Alps during the 2014-2015 winter season. These measurements and the model implementation are described in an extensive manner including decision schemes and model parameterization. Instead of integrating in detail the specific snow management practices of one particular ski resort (Hanzer et al., 2014), this development aims to build a tool able to simulate the snow conditions for a wide range of resorts and geographical areas (François et al., 2014), and thus requires a rather generic formulation if possible. We tested the sensitivity of the model to the values of parameters and evaluated the results of simulations with respect to in-situ observations.

4.2 Material and methods

4.2.1 In-Situ observations

Ski patrols from four specific resorts located in the Northern French Alps (Tignes, Chamrousse, Autrans and Les 2 Alpes) helped us to perform measurements during the 2014-2015 winter season (Table 4.1, Figure 4.1), covering a large range of meteorological conditions and operators' habits and means.

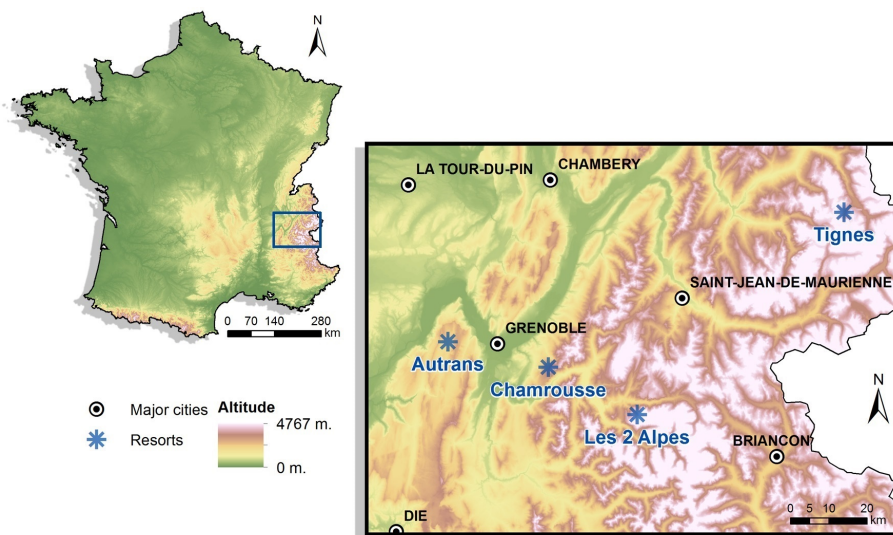


FIGURE 4.1 – Location of the ski resorts around the city of Grenoble (France) : Tignes (Haute-Tarentaise), Chamrousse (Belledonne), Autrans (Vercors) and Les 2 Alpes (Oisans).

Observations Sites

Three observation sites with natural snow conditions (Reference site), grooming and packed and skied snow conditions (Site G) and grooming plus snowmaking and skiing (Site SM) were chosen in

each resort with the aid of ski patrollers. All three sites within a given ski resort are located as closely as possible to each other and are easy to access. In every case local topography consists of flat or almost flat areas with as little wind disturbance as possible. None of the sites are in erosion or accumulation areas. However all sites are located in mountain areas where the wind may always play a significant role and be a factor of uncertainty.

Resort	Lat.	Lon.	SAFRAN massif	Altitude range (m.a.s.l)	Resort Category
Tignes	45°26 N	6°53 E	Haute-Tarentaise	1550 - 3456	Very Large
Chamrousse	45°6 N	5°53 E	Belledonne	1400 - 2253	Large
Autrans	45°12 N	5°33 E	Vercors	1000 - 1630	Nordic Ski
Les 2 Alpes	45°0 N	6°7 E	Oisans	1300 - 3568	Very Large

TABLE 4.1 – Main features of the four ski resorts where we carried out our 2014-2015 winter season field campaign. Resorts categories from François et al. (2014).

Snowmaking data on SM sites

The most likely surface on which MM snow was spread (S_{mid}) was calculated from ski slope edges, snow gun distribution on the ski slope, in-situ observations and interviews with professionals. For example in Tignes, snow guns are equally distributed on “Double M” ski slopes and the distance between them is 67 m. The width of the site SM is 36 m, resulting in a 2400 m² surface. Assuming an uncertainty of ± 400 m² i.e. $\pm 17\%$ on the surface (an uncertainty of about 8% concerning length and width), the resulting range on the surface is $S_{min}=2000$ to $S_{max}=2800$ m² (the minimum and maximum surfaces on which MM snow could have been spread respectively). Similar treatments were applied in other resorts (Table 4.2).

The uncertainty on spreading surfaces is shown in figures (section 4.5) as an envelope (corresponding to simulations using S_{min} and S_{max}) around the standard simulation (which uses S_{mid}).

Resort	Total Water Volume (m ³)	Observed Average Water Flow (Q_{MM} , m ³ h ⁻¹)	Distribution (%)				Snow Spreading Surface (m ²)		
			NOV	DEC	JAN	FEB	S_{min}	S_{mid}	S_{max}
Tignes	2317	12.2 (AW)	29	71	0	0	2000	2400	2800
Chamrousse	2322	15.6 (F)	0	100	0	0	3400	4250	5100
Autrans	662	10.5 (AW)	0	100	0	0	1800	2400	3000
Les 2 Alpes	6000	13.0 (2 × AW)	25	33	33	9	6000	7500	8500

TABLE 4.2 – Snowmaking data for the 2014-2015 winter season for all four SM sites (snowguns data). S_{min} , S_{mid} , S_{max} are respectively the minimum, the most likely and the maximum surfaces on which MM snow was spread. “AW” stands for air-water gun and “F” for fan gun.

Measurements

A measurement protocol was instigated in order to deliver a maximum amount of information within the available time and means.

- Snow depth (SD) was measured once a week by ski patrollers, on each site. Depending on local topography several measurements were made for each site so as to provide reliable integrated

results as well as an indication of the deviation of measurements.

- The average density of the snowpack was measured once a month on each site. We used a Polar Ice Coring Office (PICO) lightweight coring auger (Koci and Kuivinen, 1984).
- The snow water equivalent of the snowpack was deduced from these observations, as the product of SD and average density .
- A complete stratigraphy of the main site SM with grooming and snowmaking was carried out every month. It included the measurement of snow layers specific surface areas (SSA), using the DUFISSS instrument (Gallet et al., 2009; Morin et al., 2013) and snow layers density (Fierz et al., 2009).

Average observations are displayed as dots on results figures (section 4.3, 4.4 and 4.5) with a surrounding envelope corresponding to \pm the standard deviation of the observations.

4.2.2 SAFRAN - Crocus model chain

Snowpack Model

The multilayer snowpack model SURFEX/ISBA-Crocus (hereafter, Crocus; Vionnet et al. (2012)) explicitly solves the equations governing the energy and mass balance of the snowpack. This is done in a detailed manner which includes internal phenomena such as phase change, water percolation, snow compaction, snow metamorphism and information concerning their impact on the radiative and thermal properties of the snowpack. The energy budget of the snowpack is explicitly solved at its two interfaces (snow/atmosphere and snow/ground) and within the vertical profile. The snowpack is discretized within up to 50 numerical layers ensuring an appropriate description of the snowpack's internal processes. The model time step is 900 s (15 minutes). Microstructure properties of snow in Crocus can be described using the following variables :

- Density (ρ) : the mass of a snow sample per unit volume (Vionnet et al., 2012) ;
- Specific surface area (SSA) : the total area at the ice/air interface in a snow sample per unit mass (Carmagnola et al., 2014) ;
- Sphericity (S) : the ratio between rounded versus angular shapes (Brun et al., 1992) ;
- Age : the time since snowfall, used to approximate the radiative impact of the deposition of light-absorbing impurities on the snow (Vionnet et al., 2012)

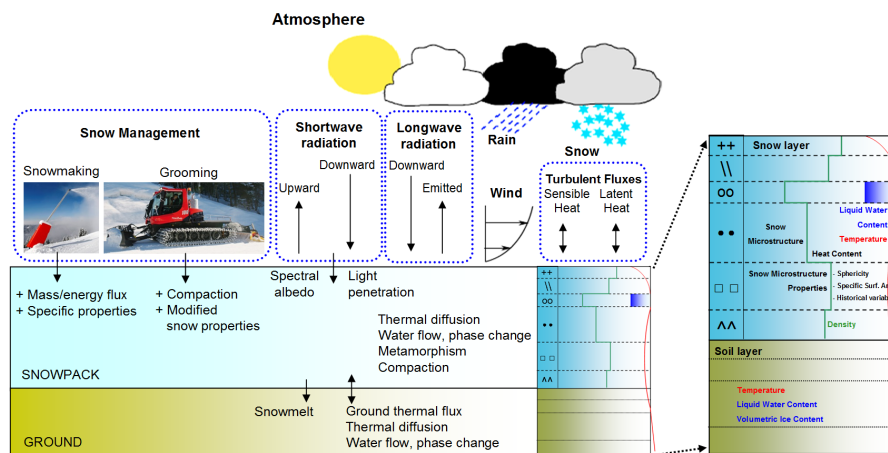


FIGURE 4.2 – The SAFRAN-SURFEX/ISBA-Crocus scheme including grooming and snowmaking effects on snowpack physics, adapted from Vionnet et al. (2012).

Meteorological Data

In French mountain regions, Crocus is usually run using outputs of the meteorological downscaling and surface analysis tool SAFRAN (Durand et al., 1993). SAFRAN operates on a geographical scale on meteorologically homogeneous mountain ranges (referred to as “massifs”) within which meteorological conditions are assumed to depend only on altitude and slope aspect. There is strong evidence from operational and research activities that the SAFRAN-Crocus model chain yields realistic results in French mountain regions in terms of integrated snow properties such as snow depth and snow water equivalent (Lafaysse et al., 2013). For a detailed review of known applications of SAFRAN-Crocus since its original development, please refer to Vionnet et al. (2012) and to the page “Crocus- Scientific applications” (www.cnrm-game.fr web site).

All simulations in this paper are based on meteorological forcing data from SAFRAN corresponding to each site (altitude, slope angle and aspect). We specifically analysed the natural snow conditions provided by SAFRAN-Crocus with in-situ observations on a local scale from ski patrollers and Automatic Weather Stations (wind, snow/rain altitude limit, precipitation amount). We fitted the SAFRAN meteorological forcing data to local conditions for each observation site. Precipitation amount and phase were modified for several precipitation events on each site : Tignes (2 modified events), Chamrousse (4), Autrans (3) and Les 2 Alpes (6). All other meteorological variables remained unchanged.

We also took into account the surrounding slopes of each site and the consequent shadowing effect (Morin et al., 2012). We used a 25 m digital elevation model (Marcelpoil et al., 2012) to create a skyline profile : for each azimuth (steps of 10°), the elevation angle of the visible sky was calculated and checked with in-situ measurements.

4.2.3 Grooming approach in the snowpack model

Our approach to artificial snow grooming consists of both an extra static load applied on the snowpack and the additional effects of the tiller applied simultaneously.

Static Stress

The natural densification of the snowpack layers is mostly driven in the model by the weight of the top layers applied to those which are deeper (Vionnet et al., 2012). The static stress applied on the snowpack due to the weight of a grooming machine (ranging from 5 to 6 kPa i.e. 500 to 600 kg m⁻²) is simply added to the weight of over burden layers (Guily, 1991; Olefs and Lehning, 2010; Howard and Stull, 2014). The deeper the snowpack, the more dampened the load (Thumlert, 2013; Pytka, 2010). We consider here the cumulated snow water equivalent instead of snow depth to assess the stress applied on a layer. Indeed, SWE combines the density (Thumlert (2013) showed that the snowmobile stress penetration in the snowpack decreases with snow density) and depth of layers as the product of both. The resulting static stress (Figure 4.3) is constant (5 kPa) for the first 50 kg m⁻² of snow e.g. the first 50 cm of fresh snow (density 100 kg m⁻³) or the first 10 cm of older snow (density 500 kg m⁻³). The stress then decreases linearly with increasing SWE until 150 kg m⁻² of snow e.g. 1.5m of fresh snow (density of 100 kg m⁻³) or 30 cm of older snow (density 500 kg m⁻³).

Tiller effect

The tiller is an additional tool mounted at the rear of a grooming machine and consists of a high speed rotating shaft (cutter bar) with multiple tines (Figure 4.4).

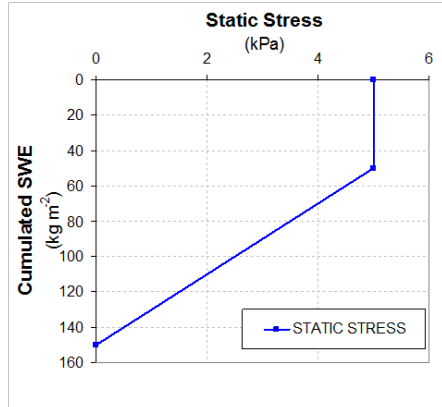


FIGURE 4.3 – The static stress applied on snow layers in Crocus when grooming is carried out



FIGURE 4.4 – The tiller is mounted at the rear of a grooming machine and consists of a high speed rotating shaft (cutter bar) with multiple tines which acts as a mixer for the top of the snowpack

Its action is basically to increase the density of the snow-by loading the snowpack with extra pressure- and to break down snow micro structure into rounded grains, which leads to higher density due to higher compacity (Fauve et al., 2002; Guily, 1991; Keddy, 1979). As a result, all impacted layers are mixed together, their properties are homogenized and some of them are modified. The effect of the tiller is simulated in Crocus by modifying the following properties of snow layers :

- Density (ρ)
- Specific surface area (SSA)
- Sphericity (S)
- Age

The tiller impacts the top layers of the snowpack within the top 35 kg m^{-2} of snow (according to the professionals) i.e. the top 35 cm of fresh snow (density 100 kg m^{-3}) or the top 7 cm of older snow (density 500 kg m^{-3}). The sensitivity of the model to this value is tested in section 4.2.3. After each grooming session the evolved density ρ_{layer}^i of impacted layers is given by :

$$\rho_{\text{layer}}^i = \text{MAX}\left(\rho_{\text{AV}}; \frac{2\rho_{\text{AV}} + 3\rho_t}{5}\right) \quad (4.1)$$

Where ρ_{AV} is the weighted average density of impacted layers before grooming, using the SWE of each contributing layer, and ρ_t (Table 4.3) is the target value the density may eventually reach through the

grooming process (Fauve et al., 2002).

$$\rho_{AV} = \frac{\sum(\rho_{layer} * SWE_{layer})}{\sum SWE_{layer}} \quad (4.2)$$

This value ρ'_{layer} is attributed to every impacted layer, simulating the mixing and densification effects of the tiller. Unless snow becomes denser than the target value (for example through humidification), it gets infinitely closer to the target density ρ_t , consistent with observations by Keddy (1979) or Guily (1991) (Figure 4.6). If ρ_{AV} is already higher than ρ_t , the model simulates a mixing effect without further densification. Eventually, the thickness of every snow layer is re-calculated with respect to the mass conservation of each layer :

$$H'_{layer} = H_{layer} * \frac{\rho_{layer}}{\rho'_{layer}} \quad (4.3)$$

The sphericity is treated in the same way (Figures 4.5). The average value of the age of snow layers is not modified, we simply attribute the average value (calculated similarly to ρ_{AV} , simulating the mixing effect). The SSA of fresh snow is generally high and decreases with snow metamorphism (Domine et al., 2007), thus the grooming effect on SSA is

$$SSA'_{layer} = MIN(SSA_{AV}; \frac{2SSA_{AV} + 3SSA_t}{5}) \quad (4.4)$$

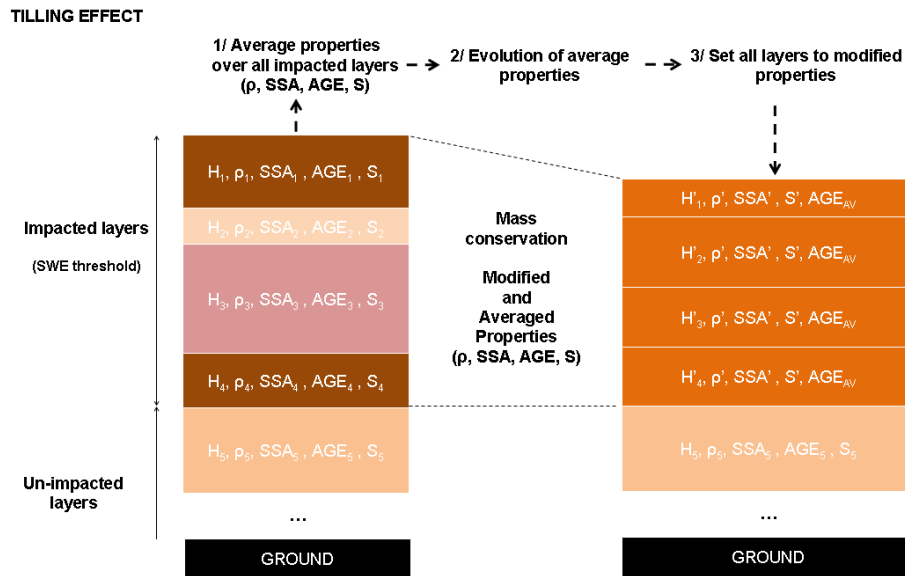


FIGURE 4.5 – The tiller effect as implemented in Crocus

The evolution of SSA, sphericity and density from equations 4.1 and 4.4 through five successive grooming sessions is shown in Figure 4.6 from two distinct initial values (one corresponds to relatively fresh snow while the other is more evolved snow). Observations from Keddy (1979) or Guily (1991) show that after 5 grooming sessions, the average density of the snow is 450 kg m^{-3} and that snow microstructure turns to small rounded grains (0.3 mm). This corresponds to an SSA of $25 \text{ m}^2 \text{ kg}^{-1}$ (Domine et al., 2007) and a sphericity of 90% (Brun et al., 1992). The resulting standard parameterization of the grooming model is :

- SWE of penetration (impacted layers) : $SWE_p = \text{top } 35 \text{ kg m}^{-2}$

Levels of Parameters	Sensitivity test Grooming parameterization				Sensitivity test Snowmaking parameterization			
	SWE _p (kg m ⁻²)	S _t (%)	SSA _t (m ² kg ⁻¹)	ρ _t (kg m ⁻³)	ρ _{MM} (kg m ⁻³)	SSA _{MM} (m ² kg ⁻¹)	S _{MM} (%)	T _w (°C)
1	50	100	15	500	650	10	100	-2
0	35	90	25	450	600	22	90	-4
-1	20	70	35	400	550	35	70	-6

TABLE 4.3 – The different parameters and values used to test the sensitivity of the model to the parameterization of snow management processes. Level (1) and (-1) correspond respectively to a higher and lower impact (or metamorphism initial condition) on snow properties while (0) is the standard parameterization (section 4.2.3 and 4.2.4). The different combinations of these levels of parameters are specified in Table 4.4.

- Target density : $\rho_t = 450 \text{ kg m}^{-3}$
- Target SSA : $\text{SSA}_t = 25 \text{ m}^2 \text{ kg}^{-1}$
- Target sphericity : $S_t = 90\%$

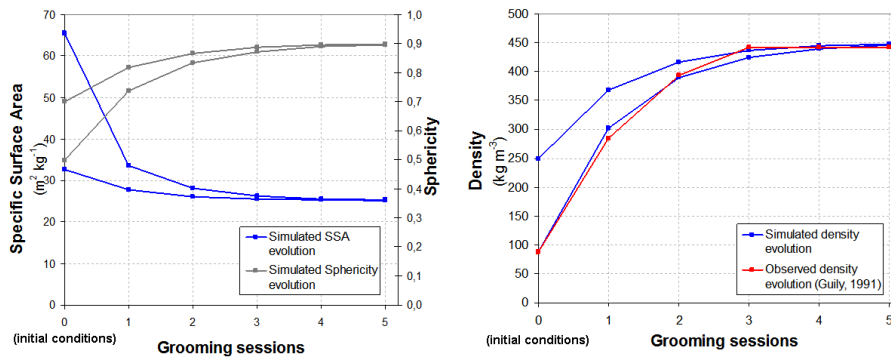


FIGURE 4.6 – The evolution in Crocus of the specific surface area (SSA), sphericity (S) and density (ρ) of impacted snow layers by the tiller after successive grooming sessions from different initial conditions. Once the target value is reached, the tiller still averages the impacted layers properties but no longer affects the average value. Only natural metamorphism (e.g. through humidification) can then increase the density and sphericity or decrease the SSA. This figure displays the evolution under the standard configuration when targets are set to $25 \text{ m}^2 \text{ kg}^{-1}$ (SSA), 90% (sphericity) and 450 kg m^{-3} (density).

Grooming schedule

Figure 4.7 describes the decision scheme : whether or not to groom. Grooming is applied in Crocus if the following criteria are true :

- Grooming period : from November 1 until resort closing date.
- Enough snow to be groomed : a minimum value of 20 kg m^{-2} of SWE i.e. 20 cm of fresh snow (density of 100 kg m^{-3}), otherwise grooming is impossible in the model.
- Working hour for grooming : 20:00 to 21:00 every day. In cases where it snows during the night, grooming is possible from 06:00 to 09:00 in the morning.

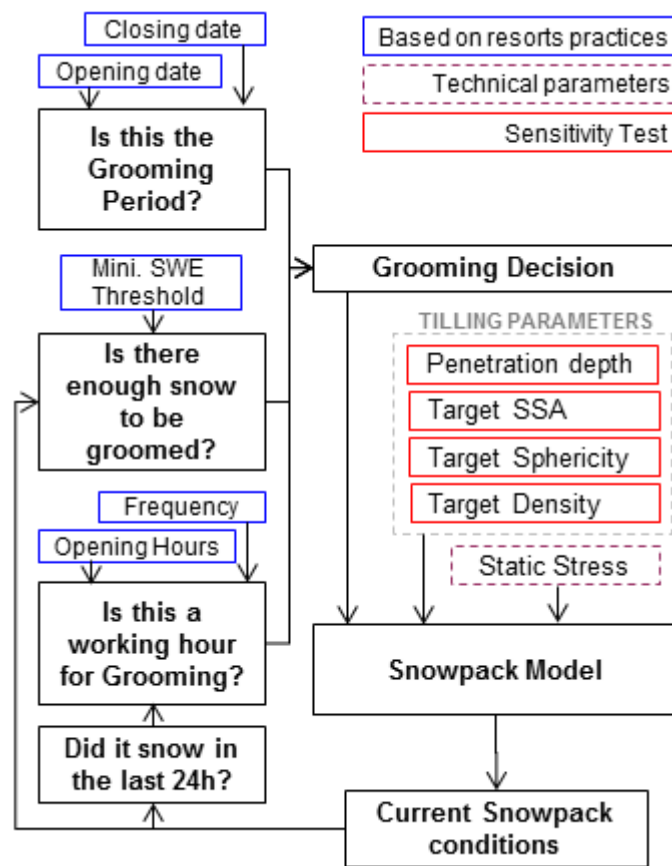


FIGURE 4.7 – Grooming approach implemented in Crocus : decision scheme and main parameters

Sensitivity test Grooming configurations								Sensitivity test Snowmaking configurations							
Configuration	G0	G1	G2	G3	G4	G5	G6	Configuration	S0	S1	S2	S3	S4	S5	S6
SWE_p	0	-1	1	0	0	0	0	ρ_{MM}	0	-1	1	0	0	0	0
ρ_t	0	0	0	-1	1	0	0	SSA_{MM}	0	0	0	-1	1	0	0
S_t	0	0	0	0	0	-1	1	S_{MM}	0	0	0	-1	1	0	0
SSA_t	0	0	0	0	0	-1	1	T_W	0	0	0	0	0	-1	1

TABLE 4.4 – Levels of parameters used for different combinations to test the sensitivity of the model to the values of parameters. The values of parameters corresponding to levels (1), (-1) and (0) are specified in Table 4.3. The configurations G0 and S0 are the standard parameterizations.

Sensitivity test of the grooming model

Seven configurations of the model parameterization are tested, combining three different levels of every parameter governing the penetration depth of the tiller (SWE_p) and the impact on each snow layer (target values S_t , SSA_t and ρ_t). Table 4.3 contains the standard value (0) and the higher (1) and lower (-1) impact values on snow properties, for each parameter. All parameters are set to the standard value (0) while the (1) and (-1) levels are sequentially attributed to each of them (Table 4.4). Levels (-1) and (1) of SSA_t and S_t are attributed at the same time to the configurations G5 and G6 since SSA and sphericity can not be viewed as independent properties

- G5 : relatively angular snow microstructure with a small “grain” size ($SSA_t = 35 \text{ m}^2 \text{ kg}^{-1}$ and $S_t = 70\%$)
- G6 : rather spherical snow microstructure with a larger “grain” size ($SSA_t = 15 \text{ m}^2 \text{ kg}^{-1}$ and $S_t = 100\%$)

4.2.4 Snowmaking approach in the snowpack model

Here we describe the snowmaking approach we implemented in the model. In order to focus on the representation of the physical processes in the model, we collected relevant data at the four observation sites (Table 4.2) and used it as input to produce snow in the model. We collected the season’s total water volume used for snowmaking (TWV) and its monthly distribution at each site (Table 4.2) which we implemented as the target production in Crocus (Figure 4.8). For example in Tignes, 29 % of the TWV (2317 m^3 , Table 4.2) was used in November (i.e. 672 m^3) and was spread over 2000 (minimum) to 2800 m^2 (maximum, Table 4.2), resulting in a target production of 240 kg m^{-2} (simulation with the minimum MM snow) to 336 kg m^{-2} (simulation with the maximum MM snow). An efficiency ratio is further applied on these amounts (Section 4.2.4).

Production decisions

Beyond the quantity of MM snow, the production decision is further dictated by simple rules (Figure 4.8), based on interviews with snowmakers and literature (Hanzer et al., 2014; Marke et al., 2014). Production is possible from November 1 until March 31. No production is allowed from 08:00 to 19:00 (opening hours). Every evening (19:00) the cumulated snow production is compared with the target. If current production is deficient then production is possible until the next morning, mimicking field practices where snowmaking facilities are generally run for the entire night rather than turned on for only a few hours. Wind speed should not exceed 4.2 m s^{-1} (15 km h^{-1}) for snow production (commonly admitted threshold). Lastly, a wet-bulb temperature (T_W) threshold is used to dictate whether or not snowmaking is triggered.

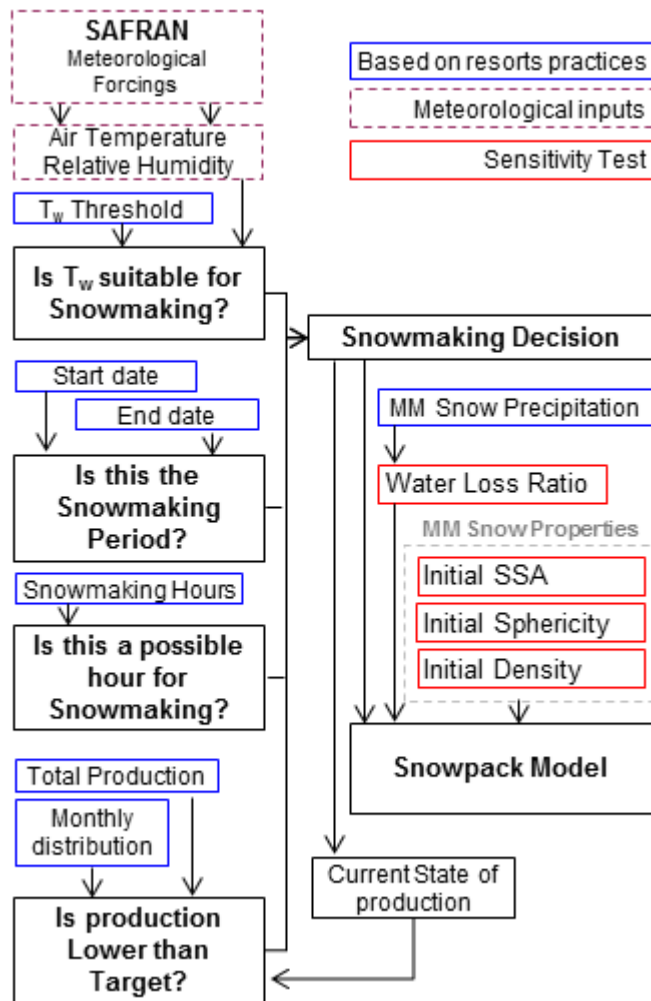


FIGURE 4.8 – Snowmaking approach implemented in Crocus : decision scheme and main parameters (see text for details).

Wet-bulb temperature calculation

The wet-bulb temperature is argued to be the most relevant criterion to determine whether or not snowmaking is possible. (Olefs et al., 2010). For convenient calculation in the model, we used the explicit method from Jensen et al. (1990) to compute T_W from the SAFRAN dry air temperature and humidity (Spandre et al., 2014). This explicit method provides consistent values of wet-bulb temperature within the range of -15 to 0°C for the dry air temperature and from 30 to 100% for the relative humidity : the maximum error compared to Olefs et al. (2010) implicit method is $\pm 0.3^\circ\text{C}$ (Olefs et al., 2010).

Machine made snow initial properties

MM snow is assumed to be small rounded grains (about 0.3 mm), falling with a density $\rho_{MM}=600 \text{ kg m}^{-3}$, a $SSA_{MM}=22 \text{ m}^2 \text{ kg}^{-1}$ (Domine et al., 2007) and a sphericity $S_{MM}=90\%$ (Fauve et al., 2002; Brun et al., 1992), accounting for the spherical nature of MM snow crystals (Table 4.3). If some natural snow falls during snowmaking, the incoming mass rate is summed with the MM snow production mass rate. The physical properties of the snowfall are then calculated from the properties of the natural snow (Vionnet et al., 2012) and the MM snow initial properties, weighted by the incoming mass rates.

Snowmaking efficiency and rate

Snowmaking efficiency The mass yield of snowmaking differs from unity, because of various effects including sublimation (Eisel et al., 1988) and transport by wind (Olefs et al., 2010). Eisel et al. (1988) found 2 to 13% water loss without accounting for wind drift while Olefs et al. (2010) mentioned a 5 to 40% total water loss. The proportion of water loss is uncertain and as far as we know no extensive field measurements were reported in the literature. Four levels of the efficiency ratio R , ranging from 100% (no water loss) to 25% (i.e. 75% of water loss) are considered here. The grooming only simulation (no production) is the case when the efficiency is $R = 0\%$. Unless specified, all simulations with snowmaking use a ratio $R = 50\%$ (standard value).

Production rate The MM snow precipitation rate (P_{MM} , $\text{kg m}^{-2} \text{ s}^{-1}$) was set at a constant value in the model on each site (Figure 4.8) and was calculated as the multiplication of the season's observed average water flow on the site (Q_{MM} in kg s^{-1} , Table 4.2) and the water loss ratio R , divided by the spreading surface of the site (S_{mid} in m^2 , Table 4.2).

$$P_{MM}(\text{site}) = \frac{Q_{MM}(\text{site}) * R}{S_{mid}(\text{site})} \quad (4.5)$$

Snowmaking model sensitivity test

Seven configurations (Table 4.3 and 4.4) were used to test the sensitivity of the snowmaking model to the parameterization for the MM snow density (ρ_{MM}), specific surface area (SSA_{MM}) and sphericity (S_{MM}) and the wet-bulb temperature threshold which triggers snowmaking (T_W). A sensitivity test of the efficiency coefficient R (ranging from $R = 100\%$ to 25%) was performed separately, using the standard configuration of the grooming and snowmaking model. All simulations with snowmaking use the standard parameterization of the grooming model (G0, Table 4.3 and 4.4).

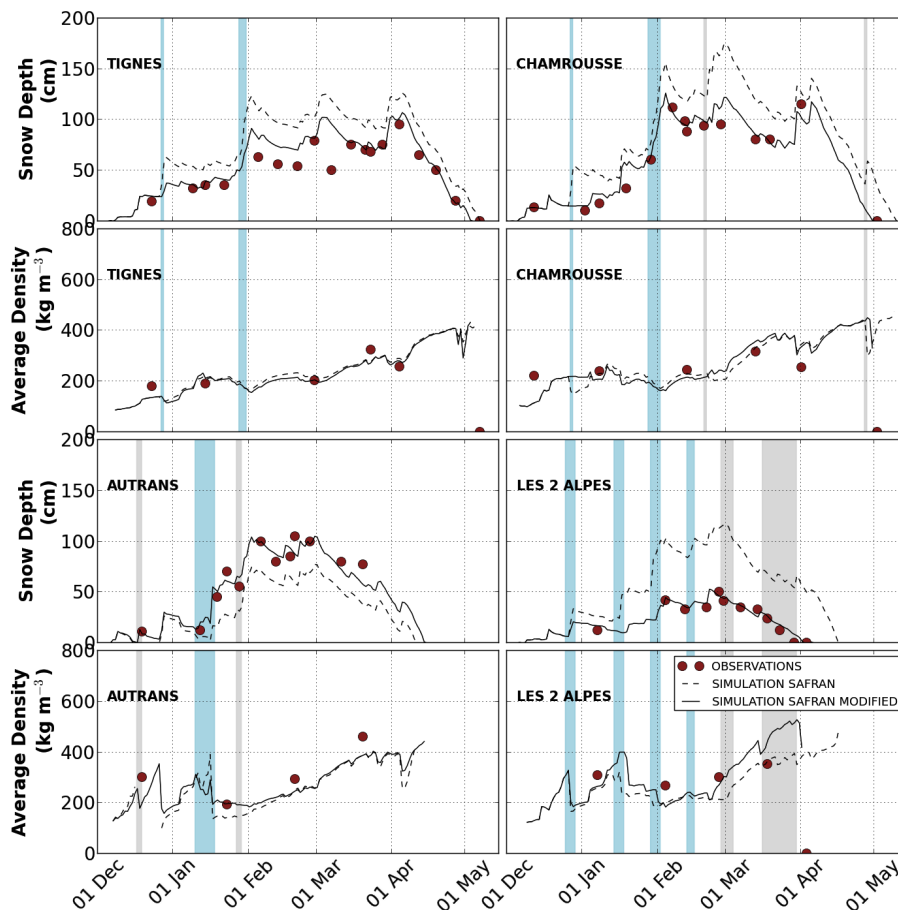


FIGURE 4.9 – Natural snow depth and snowpack average density with respect to in-situ observations (Natural snow site). Runs using SAFRAN forcing data and modified SAFRAN forcing data are shown (Section 5.2.4). The colour blue shows events when the precipitation amount was modified (due to wind drift or mis-estimation of the precipitation amount by the model) while the colour grey shows events when the phase of precipitation (snow/rain) was modified.

Resort	Tignes			Chamrousse			Autrans			Les 2 Alpes		
	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)
Nb. of Observations	18	6	6	14	6	6	12	4	4	12	5	5
SAFRAN	30	60	31	33	108	181	27	141	47	54	131	188
SAFRAN MODIFIED	14	19	30	10	30	59	8	81	66	5	23	61

TABLE 4.5 – RMSD of simulated natural snow conditions with respect to in-situ observations (natural snow site) for snow depth (SD), snow water equivalent (SWE) and density. We display the results of runs using SAFRAN forcing data and modified SAFRAN forcing data with daily observations (wind, precipitation, temperature) close to the study area.

4.3 Natural Snow : observations and simulation results

Observations By December 1st, none of the observation sites had natural snow cover yet (due to relatively dry and warm conditions in the early season, Figure 4.9). Significant snowfall occurred during the Christmas holidays and in January, within short periods of intense precipitation. The wind significantly eroded this natural snow on several occasions.

Natural snow conditions simulated by SAFRAN-Crocus are shown in Figure 4.9 along with in-situ observations (snow depth and average density). SAFRAN forcing data and modified SAFRAN forcing data (Section 5.2.4) were used. Table 4.5 contains the calculated Root Mean Square Deviation (RMSD) of these two runs with respect to the mean of the observations. The modified forcing data improves SAFRAN-Crocus accuracy, particularly when the snowpack is very thin (e.g. in Les 2 Alpes). SAFRAN-Crocus provides realistic results for the snow depth (SD), snow water equivalent (SWE) and average density with errors similar to Essery et al. (2013) : about 30 kg m⁻² for SWE and 10 cm for SD. Simulations investigating grooming or snowmaking effects on the snowpack were systematically forced by the modified SAFRAN meteorological data.

4.4 Grooming : observations and simulation results

No observation sites with groomed ski slopes only (sites G) were opened to skiers during the Christmas holidays. Groomed snowpack conditions simulated by Crocus are shown in Figure 4.10 along with in-situ observations (snow depth and average density). All seven configurations of the sensitivity test (Table 4.3 and 4.4) are shown as well as the simulation using the static load alone (no tilling effect) and the natural snow simulation. The grooming model yields more realistic simulations of the average density of the groomed slopes than the natural simulation (Table 4.6). The grooming model is also closer to observations than the static load simulation. Grooming significantly enhanced the snowpack density (Figure 4.10) and made the average density steadier than in natural snow conditions, ranging between 400 to 500 kg m⁻³. However, regarding the deviation of all grooming configurations and the uncertainty of the observations, it is impossible to conclude which configuration provides better results.

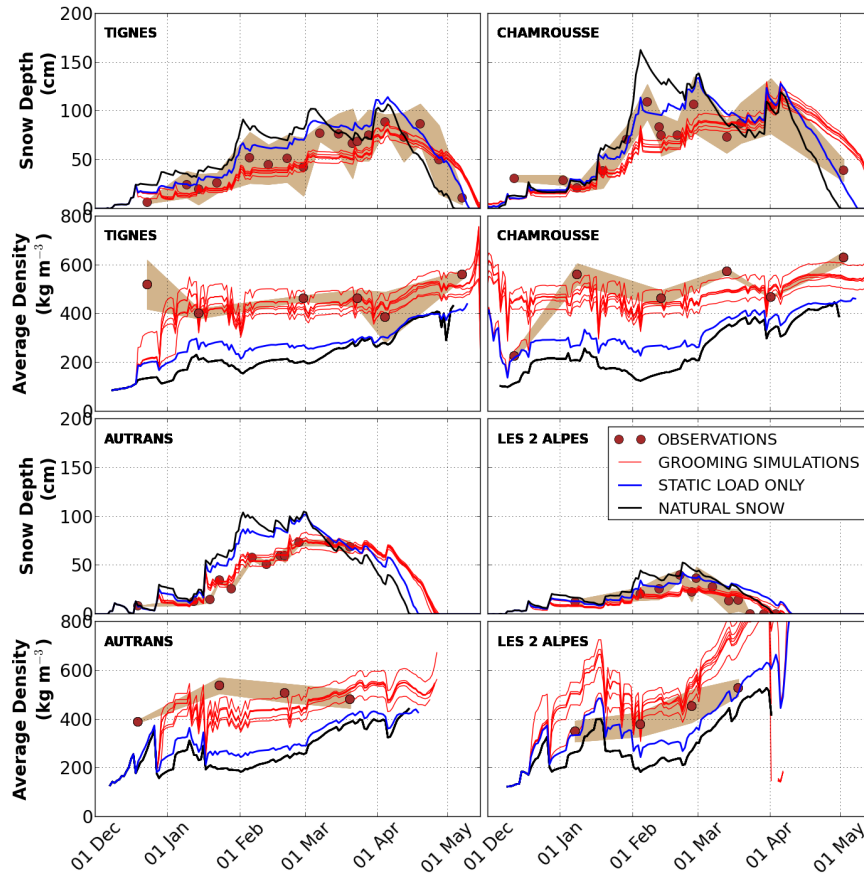


FIGURE 4.10 – Grooming impact on snowpack properties (snow depth, average density). All seven configurations of the sensitivity test (Table 4.3 and 4.4) are shown as well as the simulation using the static load alone (no tilling effect) and the natural snow simulation. The brown envelope corresponds to \pm the standard deviation of observations around the average value.

Resort	Tignes			Chamrousse			Autrans			Les 2 Alpes		
	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)	SD (cm)	SWE (kg m ⁻²)	Density (kg m ⁻³)
RMSD												
Nb. of obs.	18	6	6	14	6	6	12	4	4	12	5	5
Std. dev. of obs.	21	94	61	17	92	25	4	41	31	8	41	44
Natural Snow	21	60	243	29	147	244	27	80	239	13	19	145
Static Load Only	14	31	190	16	81	181	21	49	195	13	43	308
Grooming std. conf. (G0)	15	63	128	20	70	110	5	36	103	9	32	149

TABLE 4.6 – RMSD of simulated groomed snowpack conditions (Grooming standard configuration G0, see section 4.2.3, Table 4.3 and 4.4) with respect to in-situ observations (Site G) for snow depth (SD), snow water equivalent (SWE) and density. The standard deviation of observations was calculated for each day and the average standard deviation over the season is contained in the line ‘Std. dev. of obs.’

The simulated profile of the top 30 cm of the snowpack (Site SM) from January 2015 until the end of the observation campaign is shown in Figure 4.11. On these dates and within the top 30 cm, we assume that there is no MM snow which is located more deeply in the snowpack from early January (section 4.5). The impact of grooming on natural snow can be observed with all seven simulation profiles : (Table 4.3 and 4.4), the static load alone, the natural simulation and the observations. The

greater homogeneity of groomed layers with respect to natural snow layers appears very clearly for both SSA and density profiles. The density values calculated by the grooming model are very consistent with observations. The model is proven to provide realistic simulations of groomed snowpack conditions and we believe it could now be used to investigate the snowpack internal physical processes which occur when grooming natural snow.

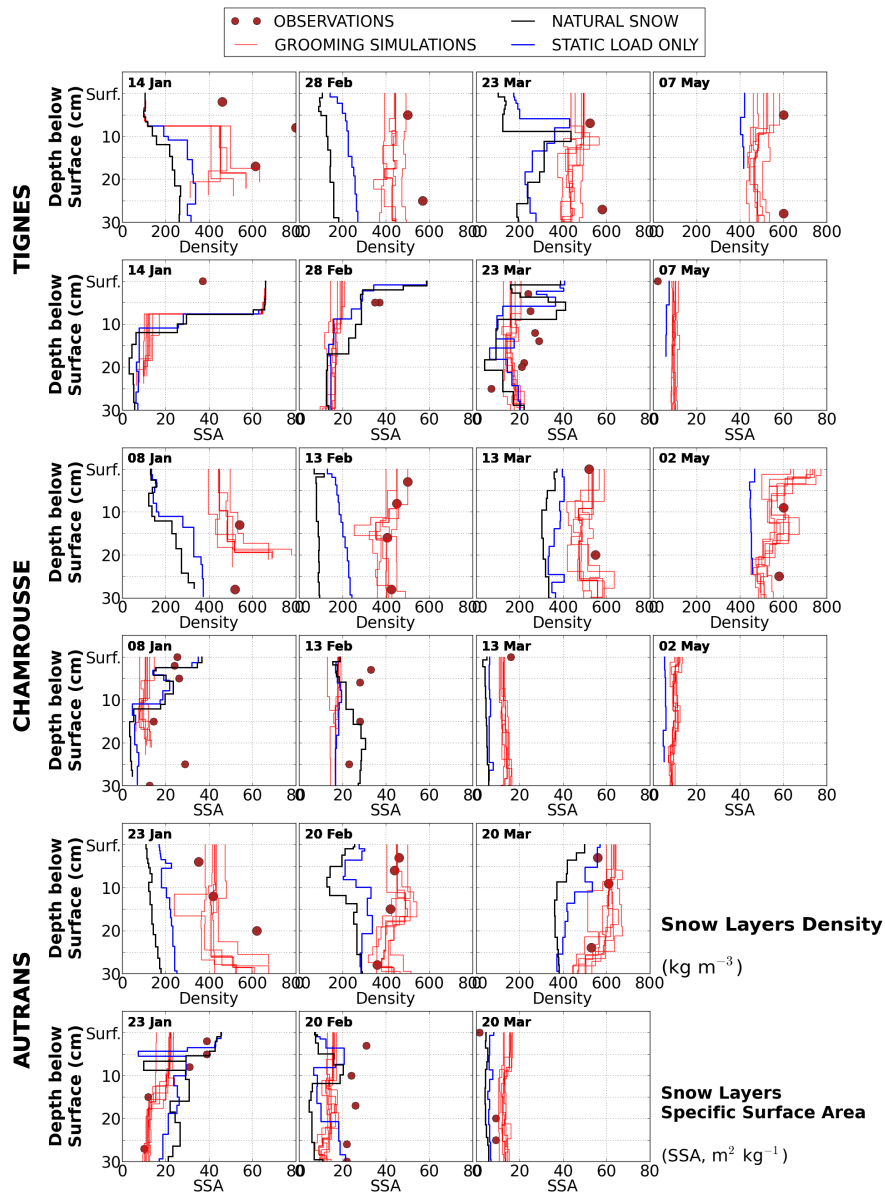


FIGURE 4.11 – Impact of grooming on SSA and density profiles within the top 30 cm of the snowpack. All seven configurations of the sensitivity test (Table 4.3 and 4.4) are shown as well as the simulation using the static load alone (no tilling effect) and the natural snow simulation. The natural snow curve does not appear in May since there is no more snow on these dates.

4.5 Snowmaking : observations, simulations and discussions

4.5.1 Evaluation of wet-bulb temperature (T_W) calculation

Observations and simulations The wet-bulb temperature calculated with the dry air temperature and relative humidity from SAFRAN was compared with local measurements by snow gun sensors (Figure 4.12). We limited the period (December 1st to February 17th) to the longest time for which sensor data were available in all three resorts (Autrans could not provide these data for technical reasons). A detailed analysis of T_W during this period showed that the measured T_W by snow gun sensors was 1 to 2 °C warmer than T_W calculated from SAFRAN data (data not shown, consistent with Figure 4.12). The cumulated time for low wet-bulb temperatures ($< -6^\circ\text{C}$) was higher with T_W calculated from SAFRAN data. The cumulated time for T_W below -10°C was very low when based on measured T_W .

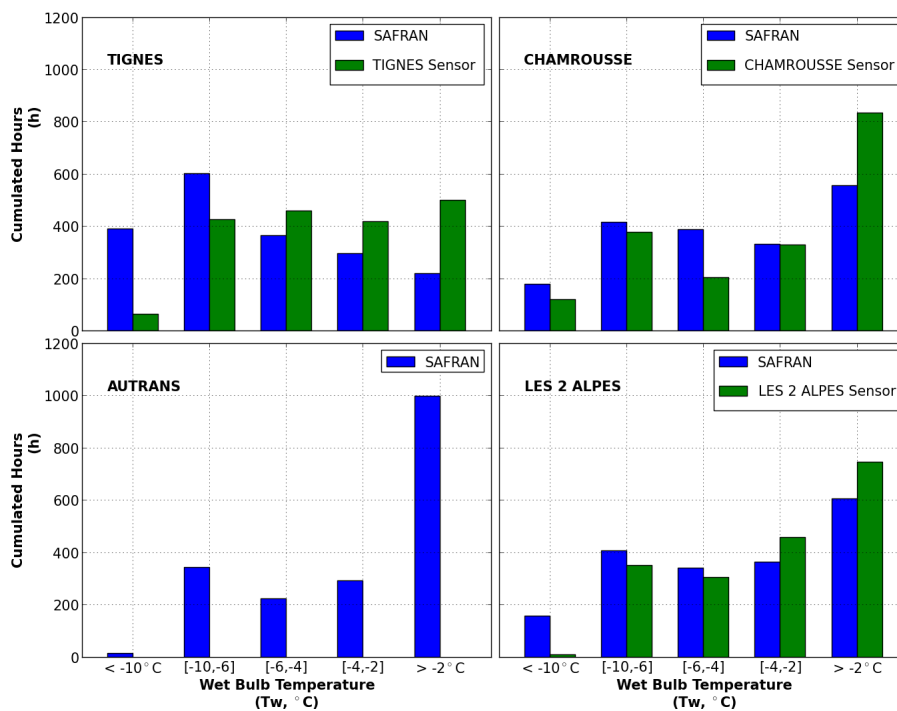


FIGURE 4.12 – Cumulated hours when wet-bulb temperature falls between specified thresholds from December 1st to February 17th. This was the longest period for which sensor data were available in all three resorts together : Tignes, Chamrousse and Les 2 Alpes. Sensor data were not available for Autrans. Calculations from SAFRAN data and the formulation by Jensen et al. (1990) are also shown for each site.

Discussion Even though these errors are significant, such differences have already been observed (Huwald et al., 2009) and are probably related in a large extent to the sensors themselves, warmer during the day when heated by solar radiation due to insufficient sheltering. Data from automatic weather stations of the official meteorological observation service (thus more protected from such sensor measurement issues) show a better agreement with data from SAFRAN than from snow gun sensors (data not shown). However, we consider that the agreement between measured and simulated T_W fulfils our expectations, i.e. to simulate snowmaking decisions in a realistic and reasonable manner.

4.5.2 Snowmaking impact on snowpack properties

Observations All ski slopes including snowmaking (sites SM) were open to skiers for the Christmas holidays, despite unfavourable snow and meteorological conditions. Most of the total production capacity was consumed by late December : Tignes, Chamrousse and Autrans did not produce MM snow after January 1st.

Simulations Table 4.7 shows the simulated production time, the average T_W (when production occurred) using the standard configuration of the model (Section 4.2.4, Table 4.3 and 4.4) along with the observed production time and average water flow (also in Table 4.2). The model may have produced up to one night more than the observations. The wet-bulb temperature (from SAFRAN) and the production history (daily amount of produced snow, in cm, assuming $\rho_{MM} = 600 \text{ kg m}^{-3}$ and $R = 100\%$) using the standard configuration of the snowmaking model (Section 4.2.4, Table 4.3 and 4.4) are shown in Figure 4.13. The timing of production is consistent with the target (Table 4.2). In all resorts a large part of the production occurred for low temperatures : the average T_W of production is below -6°C in every resort (Table 4.7).

	Simulated Production time (h)	Observed Production time (h)	Simulated Average T_W ($^\circ\text{C}$)	Observed Average water flow (Table 4.2, $\text{m}^3 \text{ h}^{-1}$)	Average water flow ($\text{m}^3 \text{ h}^{-1}$) by means of the equations by Olefs et al. (2010)
Tignes	195	190	-6.5	12.2	8.6
Chamrousse	157	149	-7.6	15.6	16.3
Autrans	65	63	-6.4	10.5	8.4
Les 2 Alpes	242	230	-6.6	13.0	8.7

TABLE 4.7 – Simulated production time and average T_W (when production occurred) using the standard configuration of the model (Section 4.2.4, Table 4.3 and 4.4) over the 2014-2015 winter season. The observed production time and the average water flow across the season are also shown. The average water flow was calculated by means of the equations of Olefs et al. (2010) with respect to the average T_W when production occurred.

The snowmaking model provides a more accurate representation of ski slopes than natural simulations but also significantly improves the results from the grooming only simulation both in terms of snow depth and average density (Figure 4.14 and Table 4.8). The deviation between the seven configurations of the model (Table 4.3 and 4.4) is low which proves that the model is consistent and reliable when faced with slight changes of the values of parameters. However, regarding the uncertainty of the observations, the question of which configuration provides better results remains inconclusive.

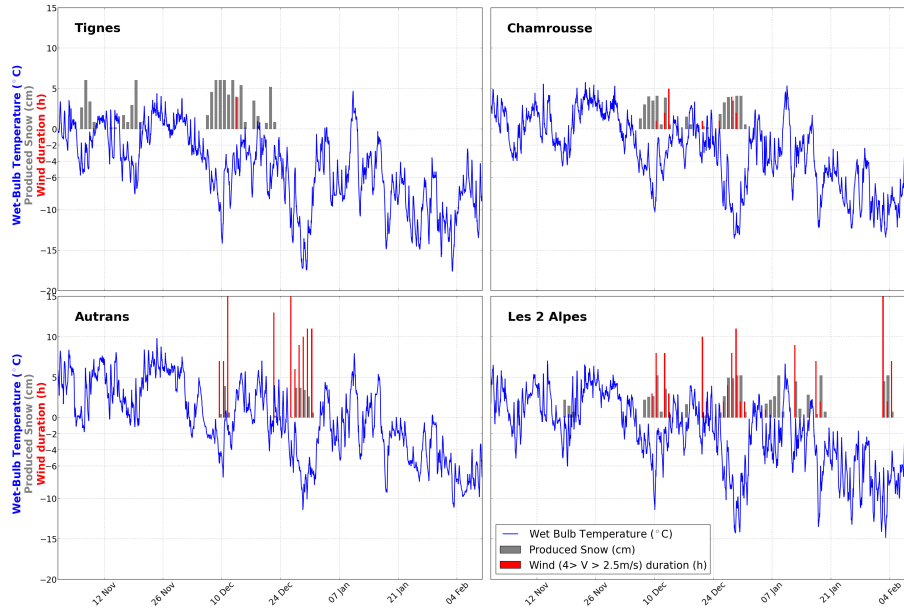


FIGURE 4.13 – Wet-bulb temperature (from SAFRAN) and simulated production history (daily amount of produced snow in cm, assuming $\rho_{MM} = 600 \text{ kg m}^{-3}$ and no water loss i.e. $R = 100\%$) using the standard configuration of the snowmaking model (Table 4.3 and 4.4). The wind duration from SAFRAN data (wind speed $4 > V > 2.5 \text{ m s}^{-1}$, in hours) is shown for days when production occurred.

The model clearly yields realistic snow layer properties (density and SSA, Figure 4.15). All SSA and density profiles from the seven configurations of the snowmaking model (Table 4.3 and 4.4) are shown with grooming only (no production) and natural snow profiles (Figure 4.15). There is no deviation between simulations within the top 30 cm, as this is groomed natural snow only (section 4.4). Below this depth, simulation results surround the observations and provide consistent results.

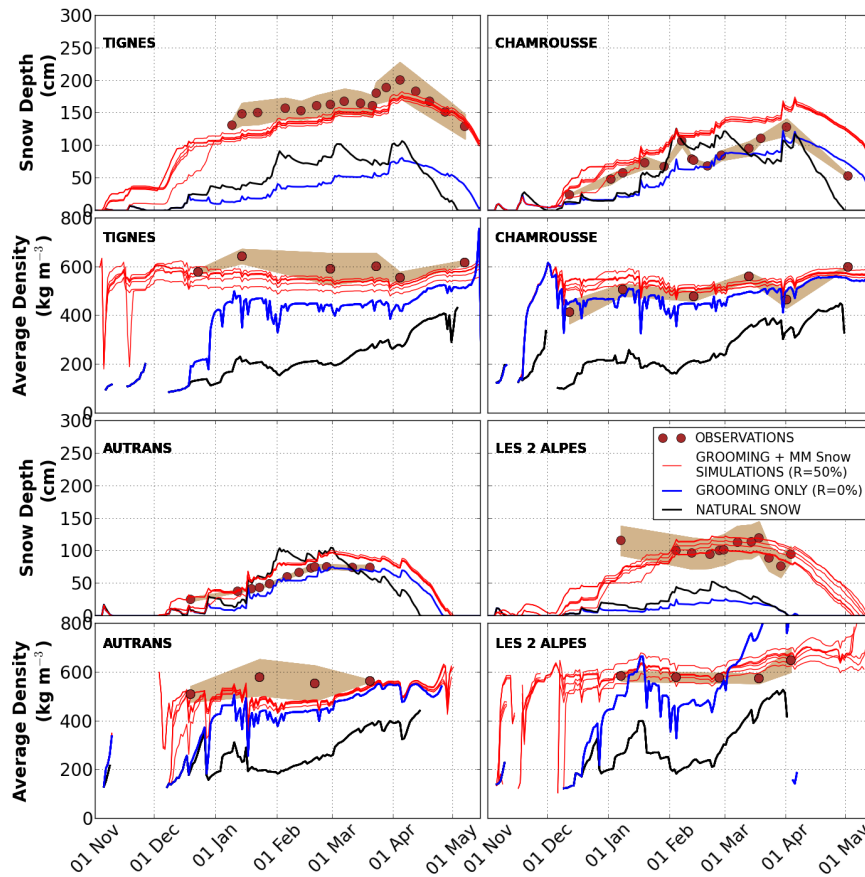


FIGURE 4.14 – Grooming plus snowmaking snowpack conditions simulated by Crocus as well as in-situ observations (snow depth and average density). All seven configurations of the sensitivity test (using a ratio $R = 50\%$, Table 4.3 and 4.4) are shown with grooming only (no production) and natural snow properties.

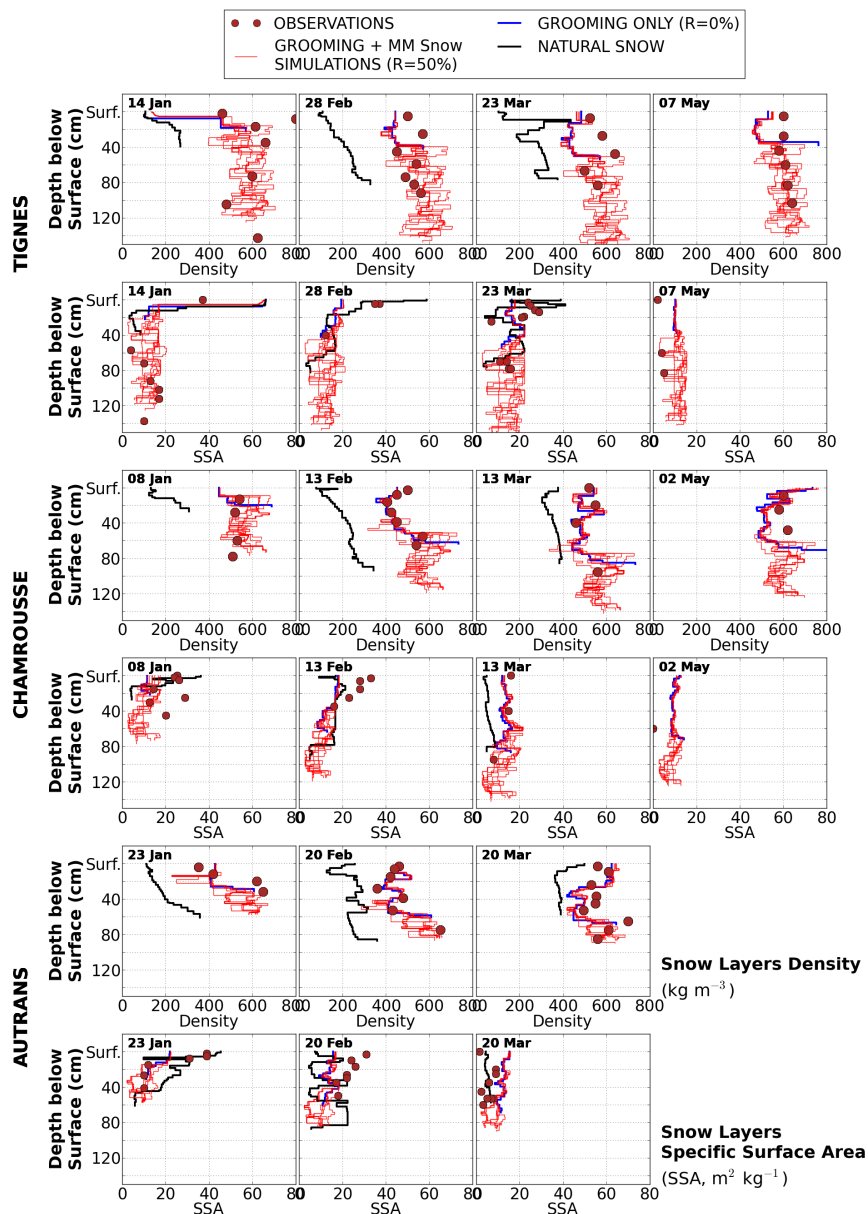


FIGURE 4.15 – Impact of grooming plus MM snow on SSA and density profiles of the top 150 cm of the snowpack simulated by Crocus along with in-situ observations. All seven configurations of the sensitivity test (using a ratio $R = 50\%$, Table 4.3 and 4.4) are shown with grooming only (no production) and natural snow profiles.

Discussion Even if neither described nor evaluated in this paper, snowmaking could be governed in the model by ongoing snowpack conditions (similarly to Hanzer et al. (2014)) and water flow derived from meteorological conditions if needed (Olefs et al., 2010). We set the values for water flow to a constant value in the model, although there is evidence that they may depend on the ongoing meteorological conditions (Olefs et al., 2010; Hanzer et al., 2014). To assess the impact of this assumption in view

of the existing knowledge, the average water flow was calculated for each site using an alternative approach. This was done by using the linear equations by Olefs et al. (2010) with respect to the simulated average temperature T_w during production periods (Table 4.7) and with comparison to the observed constant value we used in the model (Table 4.2 and Equation 4.5). The equations by Olefs et al. (2010) provided significantly lower water flow values than the observations in Tignes, Autrans and Les 2 Alpes (air water guns, Table 4.7). A good agreement was found in Chamrousse (fan gun, Table 4.7). For example in Tignes, the simulated average temperature T_w from SAFRAN when production occurred was -6.5°C , resulting in an average water flow of $8.6 \text{ m}^3 \text{ h}^{-1}$ (equations by Olefs et al. (2010) for air-water guns) while the observed water flow was $12.2 \text{ m}^3 \text{ h}^{-1}$ (Table 4.2). Hanzer et al. (2014) calibrated the coefficients of the linear relation by Olefs et al. (2010) between the water flow and the temperature in order to match the official product specifications. However this is specific to one snow gun brand and type and may not be used in other situations. Lastly, the uncertainty related to water flow is not the main issue regarding snowmaking efficiency (Table 4.8, section 4.5.3).

4.5.3 Snowmaking efficiency ratio

Observations and simulations The best agreement (based on RMSD) between observations and simulations (section 4.2.4, Table 4.8) was found for an efficiency ratio R of 50% to 75% in Tignes, 50% to 25% in Les 2 Alpes, 25% to 50% in Chamrousse and Autrans (Figure 4.16 and Table 4.8). Even though we expected from literature (Olefs et al., 2010; Hanzer et al., 2014) that the wind and sublimation would significantly decrease the amount of water converted into MM snow on the ski slopes, the observed efficiency is lower than expected. Olefs et al. (2010) mentioned a water loss ranging between 15 and 40 % for air water guns while Eisel et al. (1988)'s assessment ranged from 2 to 13% not accounting for wind effects.

Resort	Tignes			Chamrousse			Autrans			Les 2 Alpes		
	SD (cm)	SWE (kg m^{-2})	Density (kg m^{-3})	SD (cm)	SWE (kg m^{-2})	Density (kg m^{-3})	SD (cm)	SWE (kg m^{-2})	Density (kg m^{-3})	SD (cm)	SWE (kg m^{-2})	Density (kg m^{-3})
Nb. of obs.	18	6	6	14	6	6	12	4	4	12	5	5
Std. dev. of obs.	21	167	38	17	59	28	4	46	54	8	154	44
Natural Snow	101	695	346	26	188	225	19	166	302	72	489	271
GSM - R=0%	117	719	220	24	106	42	13	115	168	83	482	146
GSM - R=25%	62	460	87	19	119	53	7	64	80	36	289	45
GSM - R=50%	21	325	65	37	236	63	13	47	66	14	142	27
GSM - R=75%	27	355	56	59	359	68	22	82	55	53	281	26
GSM - R=100%	65	516	44	82	487	71	32	132	44	95	498	22

TABLE 4.8 – RMSD of simulated grooming plus snowmaking (GSM) snowpack conditions with respect to in-situ observations (Site SM) for snow depth (SD), snow water equivalent (SWE) and density. The standard deviation of measurements was calculated for each day of observation and the average standard deviation over the season is contained in the line ‘Std. dev. of obs.’. The efficiency ratio R is shown for each run, from 0% (no production) to 100% (no water loss).

Discussion Our results point out that the most uncertain parameter for correctly simulating snow properties on ski slopes is the snowmaking efficiency ratio. In comparison with it, all other processes and parameters have a limited impact on the model's ability to simulate realistic conditions on ski slopes. Accurate estimations of water loss during snowmaking can not be provided due to the uncertainty of our observations (also dependent on the meteorological conditions of the 2014-2015 winter season). However, there is a clear distinction between the situations experienced by all four resorts during the

winter of 2014-2015 (Figure 4.13) in which the wind may have an important role to play by significantly affecting the amount of snow reaching the ground (Pomeroy et al., 1993), particularly if slopes are surrounded by forests (Pomeroy et al., 1998). The best efficiency ratio is in Tignes where no windy conditions occurred during snow production (Figure 4.13, there is no vegetation either). On the contrary the worst ratio is in Autrans where windy conditions occurred for every production day and where all ski slopes are surrounded by forests. To the best of our knowledge, no extensive observation of the efficiency of snow guns has ever been reported and more detailed observations are strongly required to provide further analysis concerning this question.

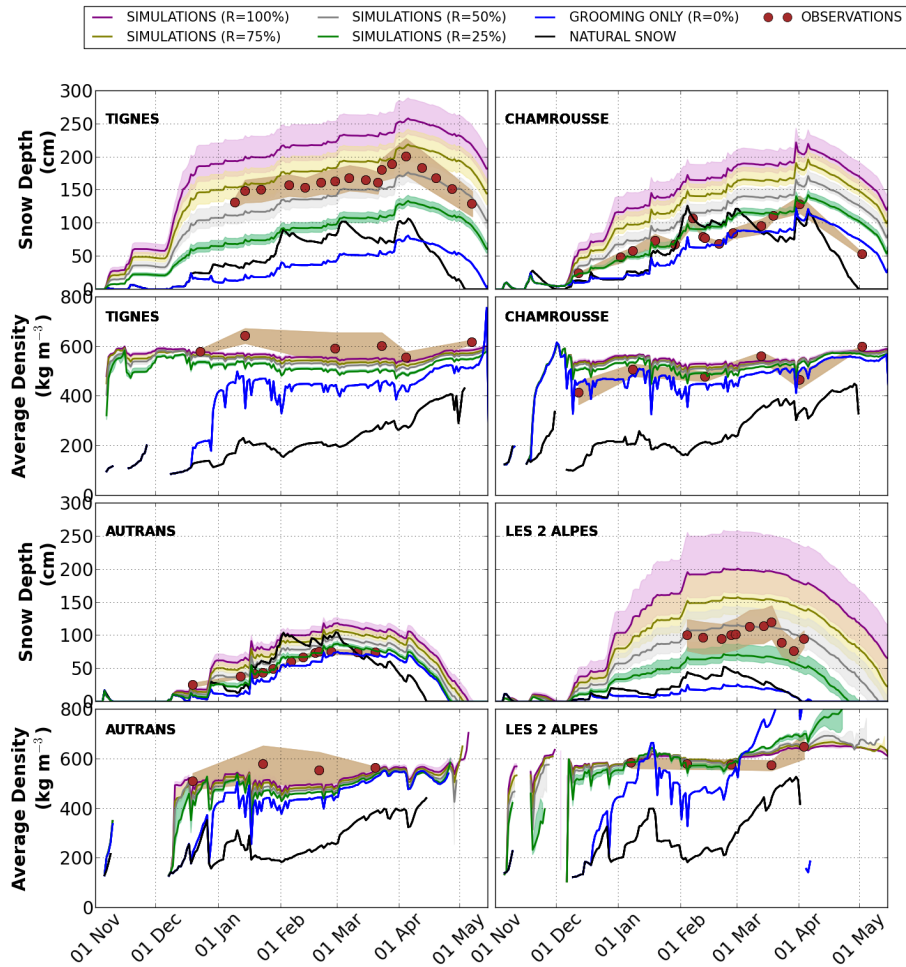


FIGURE 4.16 – Grooming plus snowmaking snowpack conditions simulated by Crocus as well as in-situ observations (snow depth and average density). All four simulations using the standard configurations (and the most likely spreading surface S_{mid}) for the grooming and snowmaking model are shown for ratios from $R = 100\%$ to 25% . Envelopes correspond to the uncertainty of the spreading surface for MM snow using S_{min} and S_{max} (Table 4.2). Grooming only (no production) and natural snow properties are also shown.

4.6 Conclusions and outlooks

Snow management processes (grooming and snowmaking) induce significant change to the physical state and behaviour of the snowpack. Here we described the integration of snow management processes (grooming, snowmaking) into the snowpack model Crocus. Comprehensive grooming and snowmaking approaches have been implemented in Crocus, based on the literature (Guily, 1991; Fauve et al., 2002; Olefs et al., 2010; Hanzer et al., 2014) and interviews with professionals. Each approach was evaluated with respect to in-situ measurements we carried out during the 2014-2015 winter season in four resorts in the French Alps and the sensitivity to the main parameters was tested.

The effect of the tiller is explicitly taken into account. Its effects on snow properties (density, snow microstructure) are simulated through their homogenization and modification, in addition to the compaction induced by the weight of the grooming machine. The sensitivity test showed that the model is consistent and reliable when faced to slight changes in its main parameters. The average snowpack density of groomed ski slopes ranges between 400 and 500 kg m⁻³ and is steadier than in natural conditions. The grooming model was proven to yield more efficiently than natural snow or even static load approach, realistic simulations of groomed ski slopes.

The specific properties of MM snow (density, specific surface area, sphericity) are taken into account in the model. The snowmaking model also provided realistic simulations of the snowpack properties with respect to observations. The sensitivity test confirmed that the model is consistent and reliable when faced to changes in parameters. The observed history of production was collected for every observation site and implemented as the production target. Even though the analysis of wet-bulb temperature showed a significant deviation between T_W measured by snow gun sensors and T_W simulated by SAFRAN, it is shown that Crocus is able to produce snow in a realistic manner with respect to the specified rules and current meteorological conditions. The snowmaking efficiency however, i.e. the ratio between the mass of machine-made snow on slopes and the water mass used for production was found to be lower than expected when consulting the literature (Olefs et al., 2010) with water loss ranging from 1/3 to 3/4 of the total water mass consumed for snowmaking. The wind and the surrounding vegetation may have a significant impact on the snowmaking efficiency (Pomeroy et al., 1993, 1998).

The main uncertainty pertains to the efficiency of snowmaking processes and further observation and investigations need to be addressed. New developments and investigations may be considered such as taking the remaining liquid water in MM snow into account or a snowmaking efficiency ratio depending on meteorological conditions (wind, T_W) and the sites' vegetation. Nevertheless, the model now referred to as "Crocus - Resort" has been proven to provide realistic simulations of snow conditions on ski slopes and may be used for further investigations. We expect to run simulations on a large scale : concerning the whole of the French Alps by coupling Crocus - Resort with a spatialized database gathering information on all ski resorts in these mountains (François et al., 2014). We also expect to provide relevant information concerning the ability of the snow industry to face meteorological variability in the present and, in the future, climate change challenges.

4.7 Evaluation of grooming in Crocus - Resort using ground temperature observations in Autrans ski resort (complementary material)

Brief introduction The major effect of grooming on snow properties is the enhancement of the density (Fahey et al., 1999; Mossner et al., 2013) and the associated thermal conductivity (Calonne et al., 2011) of the snow, leading to significantly modified thermal behavior of the snowpack with lower temperatures of the ground and increased frequency of soil frost (Kattelmann, 1986; Rixen et al., 2004). Rixen et al. (2004) reported the most detailed observations from ten sites in Switzerland with ground temperatures records under artificial and natural groomed snow with respect to control slopes (natural snow, no grooming) from October 1999 to June 2000. An average -1.2°C difference was measured between groomed natural snow and off-piste control slopes with the lowest temperatures under groomed natural snow (Rixen et al., 2004). The number of frost days was also higher under groomed natural snow although depending on the altitude of the slopes. The production of additional machine made snow provided a higher insulation capacity of the snowpack resulting in lower differences limited to a maximum -0.5°C compared to off-piste control slopes. The evaluation of Crocus-resort with respect to the thermal behavior of the snowpack under groomed slopes is highly relevant to address the capacity of the model to account for such modified properties. We therefore intended in the present section ¹ to evaluate the capacity of Crocus - Resort to simulate the groomed snowpack thermal behavior.

Material and methods The observations were realized during the 2015 - 2016 winter season in Autrans ski resort, under the exact conditions described in section 4.2.1. Snow depth and snow water equivalent were frequently observed, either by ski patrollers or the research team. Miniature temperature loggers iButtons[®] (DS1921G, datasheet on www.maximintegrated.com/en/products/digital/data-loggers/DS1921G.html) were used to measure the snow - ground interface temperature continuously from the 21 November 2015 (first natural snowfall) to the 10 May 2016. Two loggers were installed under the natural snowpack (control) and another two under the groomed natural snowpack (on-piste). The loggers were installed on the ground i.e. within the first cm of snow with a record time step set to 2 h. Such data loggers (about 1 cm diameter, 1 cm thick) have already been used for a wide range of research applications (Holden et al., 2013; Hasselberg et al., 2013), and are run by internal batteries with capacity over one year and accuracy better than 0.5°C .

Observations The temperature at the snow-ground interface (TG) was recorded by the two loggers under the control site and by one of the two under the ski slope with the second one failing, probably due to water entering the plastic protection. The difference between the two loggers under the natural snowpack was lower than 0.1°C on average over the season, which we considered as the precision of the present study (uncertainty on temperature). The two loggers provided consistent evolutions under frost occasions. The mean seasonal temperature under the control site was -0.1°C with soil frost (TG below 0°C) during about 20% of the period. Under the groomed snowpack, the observed temperature showed a maximum of 0°C with more intense and numerous frost periods : an average value of -0.9°C was observed over the season i.e. a temperature difference of approximately -0.8°C with the control

1. Observations within this section were realized during the 2015 - 2016 winter season in Autrans ski resort and analyzed by Martin Lejeune, master student in Polytech Chambéry (Université Savoie Mont Blanc) during a two months internship under my supervision from May to July 2016. The complete report of his internship can be accessed here : (French) http://www.cnrn-game-meteo.fr/IMG/pdf/20160624_rapport_martinl_cen.pdf

temperature. The soil surface was frozen approximately 70% of the period.

Evaluation of simulated temperatures The natural snow and groomed snow conditions were simulated by the model (Figure 4.17), providing two distinct simulations using the meteorological forcing data from SAFRAN as described in section 5.2.4. The groomed snowpack density was 518 kg m^{-3} (Figure 4.17) and 266 m^{-3} for the natural snowpack density. The average TG under natural snow as simulated by the model was -0.07°C with a RMS of the residuals with respect to observations of 0.6°C . The RMS of the residuals between the simulated versus the observed daily minimum temperature TG was about 0.15°C . Under groomed natural snow, the fraction of the period with soil frost as simulated by the model was consistent with observations ($70\% \pm 5\%$). The simulated average TG was -0.49°C i.e. an underestimation of the soil frost by the model (average difference to the observations $+0.4^\circ\text{C}$, RMS of residuals 1.3°C). The simulated daily minimum of TG showed an average difference with observed daily minimum of $+0.45^\circ\text{C}$ (RMS of residuals 0.8°C). The impact of grooming on the thermal regime of the soil (-0.8°C observed on average) is underestimated by the model with a simulated difference of -0.4°C .

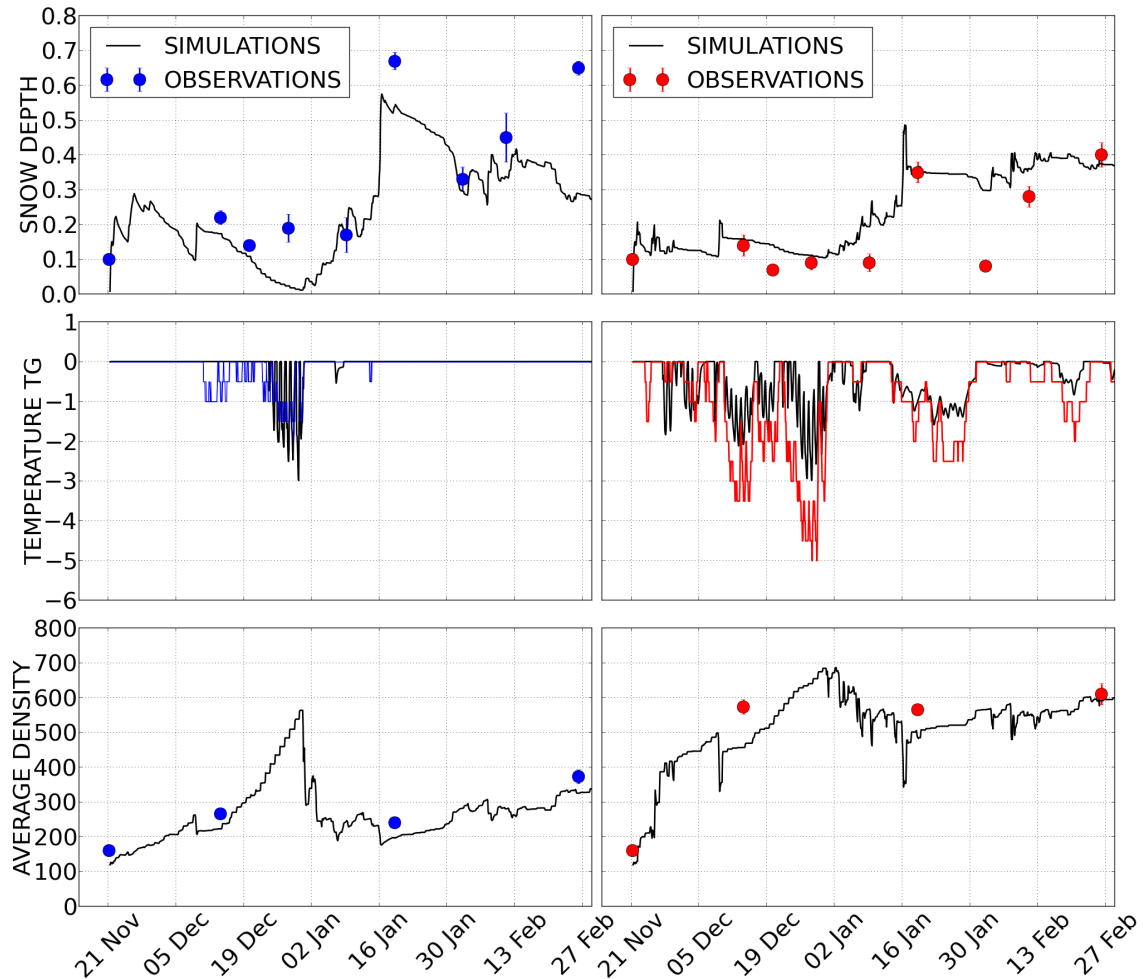


FIGURE 4.17 – Observed temperatures at the snow-ground interface in Autrans ski resort under the control natural snow cover (left panels, blue) and groomed snow (right panels, red).

Discussion and conclusions More accurate temperature loggers compared with those used in the present study may have provided evidence of the impact of grooming with more details. It would have been relevant to have more loggers on each site to address the spatial variability of the TG temperatures and assess the uncertainty related to the loggers themselves. Similar observations could also have been undertaken accounting for the production of machine made snow and compared with results from Rixen et al. (2004). However the grooming approach as implemented in the model provided relevant information on the thermal regime under a groomed snowpack. The periods with soil frost were consistent with the observations, confirming that grooming strongly enhances the fraction of time when soil is frozen (20% under natural snow versus 70% under groomed snow). In our case, the freezing intensity is also simulated with average temperatures significantly lower when accounting for grooming, consistently with findings from Rixen et al. (2004), although underestimating the temperature difference. The grooming parameterization (Section 4.2.3) therefore appears to have a consistent impact with observations on the thermal regime at the interface between the snow and the soil.

Chapitre 5

Determination of snowmaking efficiency on a ski slope from observations and modelling of snowmaking events and seasonal snow accumulation

This chapter corresponds to the paper by Pierre Spandre, Hugues François, Emmanuel Thibert, Samuel Morin et Emmanuelle George-Marcelpoil, “Determination of snowmaking efficiency on a ski slope from observations and modelling of snowmaking events and seasonal snow accumulation”, The Cryosphere Discussions, doi :10.5194/tc-2016-194

The section 5.6 is a complementary material to the above paper that was realized within the same observations sessions although the topic fell beyond the scope of this paper though fully in the scope of this manuscript.

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5.1 Introduction

Snow is essential for the ski industry (Fauve et al., 2002). It encourages ski lift operators to increase the amount of grooming and snowmaking methods so as to lessen their dependency on the variability of snow conditions. (Durand et al., 2009b; Hughes and Robinson, 1996). Snowmaking has been the main concern of recent investigations concerning the impact of climate change on the ski industry (Scott et al., 2003; Hennessy et al., 2007; Steiger, 2010; Pütz et al., 2011; Damm et al., 2014). To the best of our knowledge however, none of these results accounted for the efficiency of the snowmaking process i.e. the actual conversion of water volumes used for the production of Machine Made (MM, Fierz et al. (2009)) snow on ski slopes. Related water losses may be significant (Eisel et al., 1990; Spandre et al., 2016c).

Water losses during snowmaking were addressed in a few studies with different approaches and investigated factors. Eisel et al. (1988) estimated consumptive water loss through evaporation and sublimation during the snowmaking process through a combination of nine field experiments (mass balance) and a theoretical approach (energy balance). They found an average of 6% water loss and a negative linear relationship between the atmospheric temperature and water loss. Hanzer et al. (2014) implemented the relationship derived by Eisel et al. (1988) in a detailed snowpack model and found that for typical snowmaking conditions, water losses due to evaporation and sublimation ranged between 2 and 13%. Eisel et al. (1990) later showed that water loss during snowmaking could not be limited to evaporation and sublimation alone. This was done through the comparison of runoffs simulated by a hydrological model with observations in six test sites in Colorado ski areas. An additional 7 to 33% loss was deduced after the initial loss (related to evaporation and sublimation), resulting in a total consumptive loss of 13 to 37%. Recently, Olefs et al. (2010) reported from interviews with professionals that water losses due to evaporation, sublimation and wind erosion were estimated as being between 15 and 40 % for air-water guns and 5 and 15% for fan guns. Spandre et al. (2016c) performed observations on four ski slopes and found a minimum water loss of over 25% with significant differences between observation sites (some exceeding 50%). He concluded that external factors (wind, topography, vegetation) probably had a significant impact on the efficiency of MM snow production.

The present study aims to provide a detailed description of the seasonal evolution of a ski slope snowpack in operational conditions with a high spatial resolution (0.5 m grid), including the additional MM snow from snowmaking methods. Equivalent water masses of MM snow piles were measured prior to any action by the grooming machines, and both snow depth (SD) and snow water equivalent (SWE) of the prepared ski slope were observed on several occasions. These observations were crossed with all available data on snow production (water flow, temperature, wind) and with the results of simulations using a detailed physically based snowpack model (Spandre et al., 2016c). This was done so as to compute the ratio of MM snow mass on the ski slope through snowmaking with respect to the water mass used for the production of MM snow (ratio defined as the Water Recovery Rate, WRR). The method is described in the first section, and includes all measurements and tests set up to characterize uncertainties related to our measurements. The retained uncertainties and the results of observations as a result of these tests are detailed in a second section and discussed.

First Natural snowfall	21 Nov.					
MM snow Obs.	23 Nov.	24 Nov.	28 Nov.	1 Dec.	21 Jan.	
Ski slope Obs.				4 Dec.	20 Jan.	6 Apr.
Resort opening / closing					5 Dec.	30 Apr.
Total melt-out						3 May

TABLE 5.1 – Dates of the field campaign carried out during the 2015-2016 winter season. “MM snow Obs.” and “Ski slope Obs.” correspond respectively to dates when observations were performed on MM snow piles and ski slope.

5.2 Material and Methods

5.2.1 Description of observations : study area

The “Coolidge” ski slope is a beginner’s trail near Les 2 Alpes ski resort, a village (Oisans range, French Alps) at an elevation of 1680 m.a.s.l. The area is mainly a west-facing and almost flat slope ($\approx 5^\circ$). It is an important slope in the resort used for skiing lessons and as a route back down to the village on skis, obliging technical services to keep it under operational condition for skiing from the opening of the resort (early December) to its closure (late April). Two distinct series of observations were carried out on this site during the 2015-2016 winter season (Table 5.1) :

- Volume measurements of single snowmaking events and the related mass. Five production sessions were observed (Table 5.1).
- Seasonal snow accumulation measurements of snow depth (SD) and snow water equivalent (SWE) on the prepared ski slope i.e. in the skiing conditions as offered to skiers. Three observations were carried out (Table 5.1).



FIGURE 5.1 – The Coolidge ski slope conditions on 4 December 2015, the day before the resort opened. Edges with unprepared areas and obstacles (trees, lift infrastructures, snowgun) of the ski slope can clearly be seen.

A single air/water gun was used for our observations. The professional snowmakers of Les 2 Alpes kindly provided all available data regarding the production of MM snow on the study site. This covers 15 min time step records of the water flow of the snowgun ($\text{m}^3 \text{h}^{-1}$), the wet-bulb temperature ($^\circ\text{C}$), the wind speed (m s^{-1}) and direction ($^\circ$ from North) measured in the vicinity of the study area. These data were used both as inputs to force the snowpack model (water flow, amount of MM snow) and as references for the analysis of the outputs of the model (same variables, wet-bulb temperature). The data also helped the characterization of the production conditions (wet-bulb temperature and wind conditions). Based on communications with the snowgun manufacturer, the uncertainty of water

volumes used for snowmaking was neglected (below 1% according to the manufacturer).

The study area was defined as being based on the local topography and the initial surface of the ski slope. The Coolidge ski slope is wide (up to 75 m from January to March). It is a relatively flat grass covered area. In such a case defining limits to the ski slope can be tricky and quite subjective. In order to be as objective as possible and consistent throughout the season we defined the following rules which were systematically applied :

- All MM snow piles were measured on the total surface where MM snow was observed, unless a major obstacle (a tree, a building) stood in the area, bypassed by us.
- The surface of the operational ski slope defined by the ski patrollers changed during the ski season by a factor of up to 1.75, depending on snow conditions. The ski slope was wider in January (6632 m²) and April (7067 m²) than on 4 December (4063 m²) since there was very little natural snow at this time. This also made the edge easier to identify (Figure 5.1). On 20 January and 6 April we collected data across the total of the marked out ski slopes even though the study area for SD and SWE calculations was consistently limited to the area defined by the edge on 4 December 2015 in order to provide comparable data. A sensitivity test of the SD and SWE concerning the study surface was conducted by considering an offset of ± 2 m from the edge. The impact on SD and SWE was computed and discussed.
- The surface considered to calculate the MM snow production rate in the model was defined as the total marked out ski slope area : the “useful” area (Figure 5.2). Beyond the initial MM snow production (late November) natural snowfall occurred and the ski slope was enlarged. The enlarged area was thereafter defined as the spreading area for MM snow.

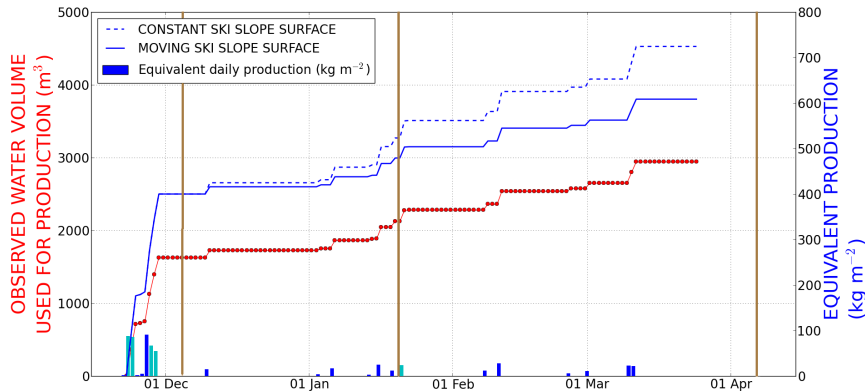


FIGURE 5.2 – Observed water volumes used for production (red) and the equivalent mass on the ski slope surface (blue). Bars stand for the daily production (bottom). Production sessions when observations were performed on MM snow piles (cyan bars) and dates when ski slope observations were carried out (light brown) are outlined.

The relationship between the average snow depth (Section 5.2) and the study surface (defined by the 2015-12-04 edge) was explored through the comparison of the calculated snow depth within the study area (4063m²) and bufferized surfaces of ± 2 m from the edge of the study area (3425 and 4749 m² respectively). Differences between a bufferized snow depth and a snow depth calculated for the study area are consistent over the three observation sessions (data not shown). The larger the surface i.e. the further the edge from the snowgun, the smaller the average snow depth. The average difference

is + 0.03 m and - 0.03 m for the smaller (- 2 m) and larger (+2 m) areas respectively, showing little variation from one observation session to another (5% relative difference maximum). This suggests that the surroundings of the study area undergo consistent evolutions throughout the season and that to address the evolution of the snowpack from initial observation the most important thing to do is to follow the exact same area. This tends to confirm that the MM snow produced after 4 December 2015 was in fact spread over the total usable surface after the slope was enlarged.

5.2.2 Snow depth measurement method and related uncertainties

Snow surface elevation point measurements

Snow surface elevation was measured on several occasions (Table 5.1) thanks to a geodetic double frequency Differential GNSS (GPS + GLONASS) Leica GS10 high precision receiver. A permanent frame was set up close to the study area on 17 November 2015 in order to provide a positioning antenna carrier at the reference station. The position of the GPS antenna once mounted on this frame was post processed to obtain the absolute position of the reference station within a few centimeters. To measure points coordinates in the investigated area, we used a rover receiver operating in real time kinematics (RTK) from the reference station. Specific points were defined (painted dots on concrete ground) and systematically re-measured during each GPS session as a control. The baseline (reference-to-rover) was less than 500 m for every single session which ensures a relative position from the reference station with a spatial (3D) accuracy below 0.02 m. The intrinsic uncertainty on the Z (altitudinal) position of the Differential GPS was 0.012 m for all of the observation sessions. The average density of points concerning the measurement of the elevation of the MM snow piles surface was 11.1 m² per point (\pm 3.3 m² per point) i.e. each point covered a surface equivalent to a 1.88 m radius disk (\pm 0.3 m). The average density for the measurement of the elevation of the ski slope surface was 16.4 m² per point (\pm 4.4 m² per point) i.e. each point covered a surface equivalent to a 2.29 m radius disk (\pm 0.31 m). The point density was adapted to the local conditions (terrain complexity), for each session i.e. the larger the changes in the snow surface, the more points were taken. This explains why the average surface per point concerning the measurement of the elevation of the ski slope surface (when snow surface is equalized by grooming machines) is larger than that of MM snow piles.

The bare ground surface elevation was also measured on 17 November 2015 in order to be compared with the snow-free helicopter-borne laser scan Digital Elevation Model (DEM) of the area acquired in November 2015. Before checking the elevation consistency between our GPS survey and this snow-free DEM, we adjusted (-0.0032 m) the elevation of our reference station on a local common levelling control point (800 m apart) provided by Institut Géographique National (IGN).

Interpolation on a regular grid

In order to compare snow surface elevations with each other or with the DEM on the bare ground, data need to be interpolated on a regular grid. The existing snow-free DEM had a spatial resolution of 0.5 m (0.25 m² pixels) which we nominated as the working grid. All data were interpolated on this grid thanks to a preliminar Triangular Irregular Network (TIN) method with a Delaunay natural neighbour triangulation (Maune, 2007). The same method was used to treat all observation sessions. Once interpolated on the working grid, all observation sessions could be compared to each other or with the bare ground, providing a spatial observation of the snow depth across the study area.

Such a method implies several sources of uncertainty (instrument, interpolation) which we intended

to assess through three distinct tests :

- a high-resolution Terrestrial Laser Scan (TLS, Prokop (2008)) was used on 1 December 2015 on a MM snow pile which we also measured with the GPS method. We were then able to compare the differences on both the GPS points alone and the interpolated GPS points with the TLS points in order to obtain the error that arises when interpolation is executed (effect of point density).
- differences with the DEM of the bare ground of both the GPS points alone and the interpolated points of the bare ground by the GPS method (17 November 2015) were calculated.
- hand made snow depth measurements were made on three occasions (observations of the ski slope) with a probe and compared with the interpolated snow depth by the GPS method.

Evaluation of uncertainties on snow depth

First of all we compared the interpolated snow surface elevations with data from a Terrestrial Laser Scan (see Appendix 5.6 for more details). An average elevation difference of - 0.012 m was measured between the interpolated GPS and the TLS snow surfaces (2018 m²). The Root Mean Square of the differences (RMSD) was 0.055 m (Table 5.2). A significant variability (standard deviation) was measured within each 0.5 x 0.5 m² pixel thanks to the TLS measurements : 0.031 m on average across the 8072 pixels. Secondly, we compared the interpolated snow-free surface elevations with the existing Digital Elevation Model of the ground. An average 0.003 m average elevation difference was measured between the GPS interpolated ground surface and the DEM data (4044 m²). The standard deviation of differences was 0.064 m (Table 5.2). Lastly, the GPS interpolated snow depth was compared with hand made measurements on several occasions (Table 5.2 and Appendix 5.6). An average - 0.008 m average difference was measured between the GPS interpolated snow depth and the manual observations. The standard deviation of differences was 0.053 m (Table 5.2).

To sum up uncertainty analyses, the average difference in the snow surface elevation interpolated from the Differential GPS points with respect to either TLS measurements or DEM data, ranged between - 0.012 and 0.003 m (Table 5.2) whilst the RMS of the differences ranged between 0.048 and 0.064 m. The distribution should statistically not be considered as being normally distributed, though distributions are close in both cases to normality (Appendix 5.6). Beyond these results we compared the interpolated snow depth with hand made measurements. The agreement was excellent (average error of - 0.008 m, RMSD = 0.053 m) and a statistically significant test for normality (Table 5.2, Appendix 5.6). Regarding the internal variability of the snow surface elevation within a pixel (0.031 m) and the sensitivity of the snow depth to the study area, we therefore considered $\sigma_{SA} = 0.03$ m as the uncertainty concerning the elevation of the snow surface. We also considered the error on the snow surface elevation to be normally distributed, which was a reasonable approximation. Consequently the combined uncertainties on the elevations of snow surfaces (σ_{SA}) to obtain the snow depth uncertainty σ_{SD} can be deduced (Bevington and Robinson, 2003) assuming errors to be uncorrelated and providing a consistent value to the calculated RMS of the differences with the comparison methods (Table 5.2) :

$$\sigma_{SD} = \sqrt{2} * \sigma_{SA} = 0.042\text{m} \quad (5.1)$$

Comparison method	Type / Session	Number of points	Average difference (m)	RMS of differences (m)
Terrestrial Laser Scan	GPS points	156	- 0.0046	0.055
	Interpolated points	8072 pixels (2018 m ²)	- 0.012	0.048
Digital Elevation Model	GPS points	145	0.032	0.047
	Interpolated points	16179 pixels (4044 m ²)	0.003	0.064
Probe manual measurements	2015-12-04	13	- 0.002	0.041
	2016-01-20	8	- 0.019	0.046
	2016-04-06	8	- 0.006	0.073
	All	29	- 0.008	0.053

TABLE 5.2 – Average difference and RMS of the differences between interpolated snow surface elevation and Terrestrial Laser Scan measurements on a snow pile (1 December 2015), between the elevation of bare ground with the GPS method and the existing Digital Elevation Model (DEM) and between interpolated snow depths and probe measurements on ski slopes (Appendix 5.6)

5.2.3 Conversion of snow volumes into snow masses

The snow density was measured in several distinct locations on MM snow piles using a dedicated snow sampler (1/2 liter) and by weighing the snow samples. We used the average density and standard deviation of all observations for the sessions when we could not perform density measurements (23 November and 1 December 2015). The uncertainty on MM snow density σ_ρ for single snowmaking events was defined as the standard deviation of all density measurements (Table 5.3). The density showed a weak variation of 4% on MM snow density (Table 5.3) from one production session to another. This supported the assumption that one use the average and standard deviation of density across all observations regardless of the dates when measurements were missing.

We also performed measurements of the average density of the snowpack on the ski slope using a PICO coring auger (Koci and Kuivinen, 1984) for each session of observations. The snowpack average density on the ski slope showed a significant increase during the season. The uncertainty on the snowpack density was defined as the variability (standard deviation) of all density measurements for each single session (Table 5.3).

Date of observation	Number of measurements	Average density (ρ_{av} , kg m ⁻³)	Standard Deviation (σ_ρ , kg m ⁻³)
Average density on MM snow piles (prior to any action by grooming machines)			
All sessions	21	437	18
Average density on the ski slope (as opened to skiers)			
2015-12-04	13	545	31
2016-01-20	8	528	37
2016-04-06	9	618	26

TABLE 5.3 – Average MM snow density for each session of observations (top) and average snowpack density observed on the ski slope for all three sessions (bottom).

Whether on MM snow piles or on the ski slope, the Snow Water Equivalent (SWE, kg m^{-2}) was computed for each point of the grid by the equation (5.2) between snow depth and density :

$$\text{SWE}_{\text{pt}} = \text{SD}_{\text{pt}} * \rho_{\text{av}} \quad (5.2)$$

The uncertainty on the SWE is computed assuming that the uncertainties on the snow depth (σ_{SD}) and density (σ_{ρ}) are independent and normally distributed (Bevington and Robinson, 2003). The uncertainty on snow depth and density are considered to be $\pm \sigma$ therefore with a standard confidence interval of 68% (Bevington and Robinson, 2003).

$$\left(\frac{\sigma_{\text{SWE}}}{\text{SWE}_{\text{av}}}\right)^2 = \left(\frac{\sigma_{\text{SD}}}{\text{SD}_{\text{av}}}\right)^2 + \left(\frac{\sigma_{\rho}}{\rho_{\text{av}}}\right)^2 \quad (5.3)$$

The uncertainty σ_{SWE} is obtained for each session thanks to the averages SWE_{av} and SD_{av} of the session by the equation (5.3). The resulting uncertainties σ_{SWE} ranged between 20 kg m^{-2} for MM snow observations and up to 35 kg m^{-2} on ski slopes.

5.2.4 Modelling of snowpack conditions on ski slope

Crocus Resort is an adapted version of the multilayer physically based snowpack model SURFEX/ISBA-Crocus (Vionnet et al., 2012). It explicitly takes into account the impact of grooming and snowmaking (Spandre et al., 2016c). Crocus Resort solves equations governing the energy and mass balance of the snowpack on the ski slope. The model time step is 900 s (15 minutes). All simulations in this paper with MM snow production include the impact of grooming on the snow. The snow management component Crocus-Resort of Crocus model (Spandre et al., 2016c) requires the setting of a series of grooming and snowmaking rules and thresholds. For grooming, we used the standard approach described in Spandre et al. (2016c). For snowmaking, Crocus-Resort can be driven either with a target production framework, or by using observed production time series as an input. In both cases, production is only possible below wet bulb temperature and wind speed thresholds, and the snowmaking efficiency, i.e. the mass of snow corresponding to the mass of liquid water used (formally equivalent to the WRR), can be specified. The default value is 1. (no water loss accounted for, see Spandre et al. (2016c)). In French mountain regions, Crocus Resort is usually run using outputs of the meteorological downscaling and surface analysis tool SAFRAN (Durand et al., 1993).

SAFRAN operates on a geographical scale on meteorologically homogeneous mountain ranges (referred to as “massifs”) within which meteorological conditions are assumed to depend only on elevation and slope aspects. All simulations in this paper are based on meteorological forcing data from SAFRAN corresponding to Les 2 Alpes site (elevation, slope angle and aspect). We specifically analysed the natural snow conditions provided by SAFRAN-Crocus Resort with in-situ observations on a local scale from ski patrollers and Automatic Weather Stations (wind, snow/rain elevation limit, precipitation amount). If relevant we adjusted the SAFRAN meteorological forcing data (amount and snow/rain phase of precipitations) to local conditions for this site. The deposition rate of dry impurities on the snowpack surface was also adapted to match the natural melting rate at the end of the season (Brun et al., 1992; Dumont et al., 2012). We also took into account the surrounding slopes of each site and the consequent shading effects (Morin et al., 2012; Spandre et al., 2016c). Lastly, the wet-bulb temperature was computed from SAFRAN dry-air temperature and specific humidity using the formulation from Jensen et al. (1990) as described by Spandre et al. (2016c).

5.2.5 Definition and computation of the water recovery rate

The Water Recovery Rate (WRR) is defined as the mass balance between the initial mass of water used for production and the resulting mass of MM snow (Equation 5.4). The WRR therefore ranges between 0 and 1, and can be expressed in % and computed either for a MM snow pile prior to any action by grooming machines or for a ski slope snowpack such as that offered to skiers.

$$WRR = \frac{\text{Mass}_{\text{snow}}}{\text{Mass}_{\text{water}}} = \frac{\text{SWE}_{\text{av}} * \text{Surface}}{\text{Volume}_{\text{water}} * \rho_{\text{water}}} \quad (5.4)$$

The SWE_{av} was computed as defined in section 5.2.3. The surface is determined by the study area. Since we neglected the uncertainty on the volume of water used for snowmaking (Section 5.2.1), the uncertainty on the WRR is related to the uncertainty on the SWE (Equation 5.5). σ_{SWE} was computed as defined in section 5.2.3.

$$\sigma_{\text{WRR}} = \sigma_{\text{SWE}} * \frac{\text{Surface}}{\text{Volume}_{\text{water}} * \rho_{\text{water}}} \quad (5.5)$$

We performed simulations of the ski slope conditions which took into account recorded production (100 % water mass, Table 5.7) and where there was no production (0% i.e. groomed only snow). We ran additional simulations using water recovery rates values prescribed to Crocus Resort below 1 and computed the RMS of the differences between the simulations and the observations. We used distinct water recovery rates for the first (20 November - 5 December 2015) and the two later periods, regarding the differences in production conditions (Table 5.7).

- We simulated snow conditions using water recovery rates from 100% to 30% with a step of 5% and compared the snow conditions (SWE, SD) with the observation on 4 December 2015. The simulations which provided conditions within the range of uncertainty of the observations were selected.
- From this initial step providing distinct potential snowpack conditions on 5 December 2015 we performed additional simulations over the second period of the season (after 5 December 2015) using various water recovery rates prescribed to Crocus Resort to determine the overall water recovery rate based on the minimum RMS of differences between simulations and observations.

5.3 Results

5.3.1 Single snowmaking events

Observations

Snow piles were usually not that far ahead of the snowgun with a significant MM snow depth at the bottom or even at the back of it (Figure 2a) in consistency with the low wind speed conditions observed in all sessions (Table 5.4), mainly originating from the East or South-East on average (wind direction not shown). All observed snow piles showed similar geometric patterns (Figures 2a and 2b) resulting in consistent distributions of the snow around the center of the MM snow piles (Figure 2b). The uncertainty on the snow volume within a distance from the snowgun was computed as the product of the surface within the circle and the uncertainty on the snow depth (error bars in Figure 2b).

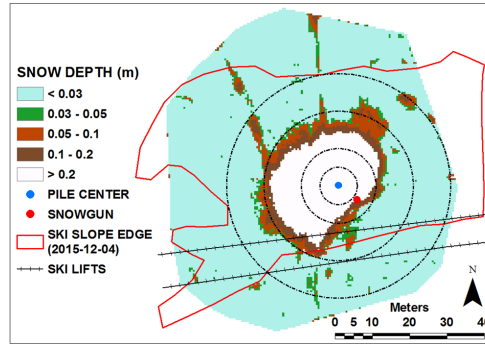


FIGURE 2a – The snow depth raster for 23 November 2015 production session along with the positions of the snowgun, the center of the MM snow pile and the concentric circles of radius $R = 5, 10, 20$ and 30 m. The edge of the ski slope on 4 December 2015 is also shown.

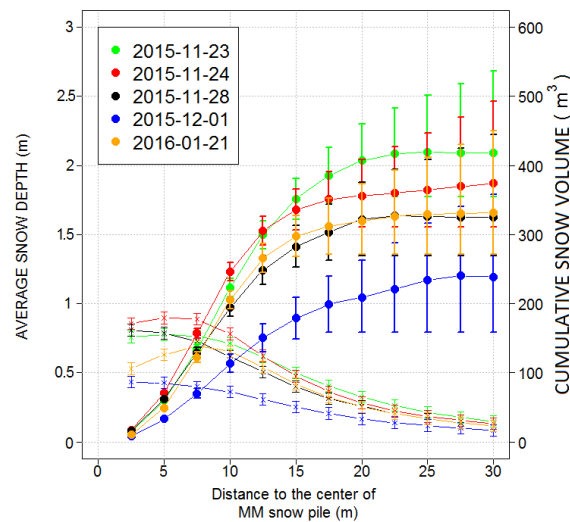


FIGURE 2b – Average snow depth (\times) and cumulative snow volume (\bullet) within concentric circles around the center of the MM snow pile of radius R from 2.5 to 30 m. The larger the circle the lower the average snow depth and thus the larger the uncertainty on the snow volume.

The average snow depth and the resulting snow volume were calculated for each session of MM snow production within concentric circles around a common fixed point. This point was defined from observations and named “center of MM snow pile” (identical for all sessions, Figure 2a). The equivalent water mass was calculated as the product of the average SWE within the considered circle (equation 5.2) and the surface of the disk inside the circle, providing the mass of water (kg).

Session	2015-11-23	2015-11-24	2015-11-28	2015-12-01	2016-01-21
Water flow (m ³ h ⁻¹)	18.4 (± 1.7)	18.2 (± 1.7)	17.1 (± 1.7)	13.1 (± 1.7)	12.4 (± 1.7)
Production duration (h)	19.6	19.2	15.8	17.3	12.0
Wet-bulb Temperature (°C)	-8.1 (± 1.5)	-8.7 (± 1.1)	-8.5 (± 1.4)	-7.5 (± 1.1)	-7.8 (± 1.7)
Wind speed (m s ⁻¹)	1.82 (± 0.8)	1.06 (± 0.48)	0.53 (± 0.53)	0.56 (± 0.47)	0.53 (± 0.58)
Recorded water volume used for snowmaking (m ³)	361	351	275	227	152

TABLE 5.4 – Detailed production conditions for every session, with the **average value** (± σ).

Water recovery rate from observations of single snowmaking events

The MM snow mass (kg) was calculated for single sessions of production from the snow volumes (m³) within concentric circles around the “center” point (Figure 2b) and the MM snow density (kg m⁻³, Table 5.3). The MM snow mass was further divided by the mass of water used for MM snow production for the given session (Figure 5.2, Table 5.4), providing the water recovery rate (WRR, %, Figure 5.3). The uncertainty on the snow mass within a distance from the snowgun was computed as defined in section 5.2.3 and divided by the mass of water used for MM snow production for the given session to provide an uncertainty on the WRR (σ in %, error bars in Figure 5.3).

Beyond a distance of 20 to 25 m from the center of the snow pile, the MM snow volume no longer increases whereas the uncertainty is considerable (over 10%, Figure 5.3). This prevents any conclusion in relation to the recovery rate including those areas. All sessions before the resort opened showed an approximate 20 to 30% water recovery rate within 10 m and 40 to 50% within 20 m (Table 5.5). The 21 January 2016 session showed similar behavior with significantly higher WRR (57 and 89% within respectively 10 and 20 m distances). Such differences are discussed further in section 5.4.

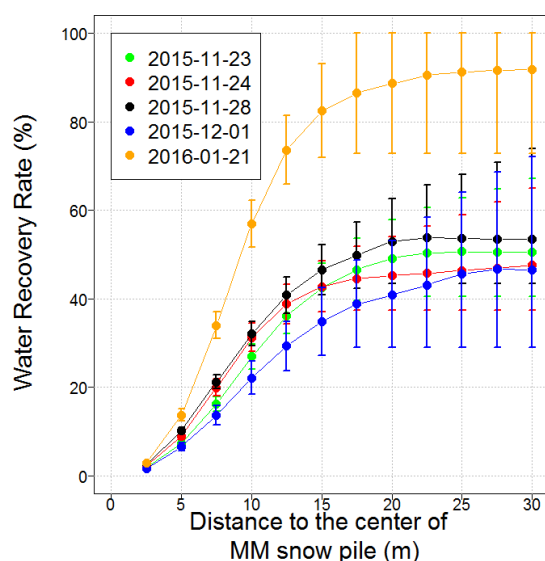


FIGURE 5.3 – The water recovery rate (%) within concentric circles around the center of the MM snow pile. The larger the circle the larger the uncertainty on the snow volume and therefore the larger the uncertainty on the water recovery rate.

Session		2015-11-23	2015-11-24	2015-11-28	2015-12-01	2016-01-21
Water recovery rate (%)	R = 10 m	26.9 (± 2.8)	31.3 (± 3.2)	32.0 (± 2.7)	22.1 (± 3.7)	56.9 (± 5.3)
	R = 20 m	49.2 (± 8.6)	45.2 (± 8.8)	53.0 (± 9.6)	40.8 (± 12.4)	88.7 (± 11.4)

TABLE 5.5 – The water recovery rate within 10 m / 20 m (**Average value** $\pm \sigma$) around the center of the MM snow pile

5.3.2 Seasonal snow accumulation

Performance of the model in simulating natural snow conditions and wet-bulb temperatures

The computation of the uncertainty on the natural snow water equivalent was based on the simulation results with and without correction of the forcing data and impurities rate (Section 5.2.4). The RMS of the differences between the simulations and the in-situ observations are highly reduced (improved simulations) when fitting the meteorological forcing data to the specificities of the site (Table 5.6). The final RMS of the differences on SWE (after corrections) is 14 kg m^{-2} and final errors on the snow depth, SWE and density are similar to Essery et al. (2013), confirming that SAFRAN-Crocus provides realistic simulations of the natural snowpack evolution once adjustments are made in albedo (impurities) and forcing data. We therefore assumed that the SAFRAN-Crocus Resort model would also provide realistic simulations of the groomed snowpack. We accounted for a larger uncertainty on the snow water equivalent of the groomed snowpack ($\sigma_{\text{SWE}} = 30 \text{ kg m}^{-2}$ i.e. 0.06 m uncertainty on snow depth for a 500 kg m^{-3} density, Spandre et al. (2016c)).

Natural snow	RMS Differences			Melt-out date
	SWE (kg m ⁻²)	SD (m)	Density (kg m ⁻³)	
Observations	N = 6 observations			2016-04-01
SAFRAN - Crocus	51	0.21	82	2016-04-06
Adjusted SAFRAN - Crocus	14	0.14	22	2016-04-02

TABLE 5.6 – Performance of the snowpack model in simulating the natural snow conditions before and after the adjusting of the meteorological forcing data and impurities rate (Section 5.2.4) quantified by the RMS of differences between model and observations.

Apart from the natural snow conditions, the cumulated time-span over which wet-bulb temperature fell within specific ranges was calculated for the MM snow production period i.e. from 20 November 2015 until 15 March 2016, both from the in-situ data recorded by the snowgun sensor and the data from SAFRAN (Figure 5.4). The distribution of the wet-bulb temperature from SAFRAN meteorological data is very consistent with the T_w distribution from the snowgun sensor.

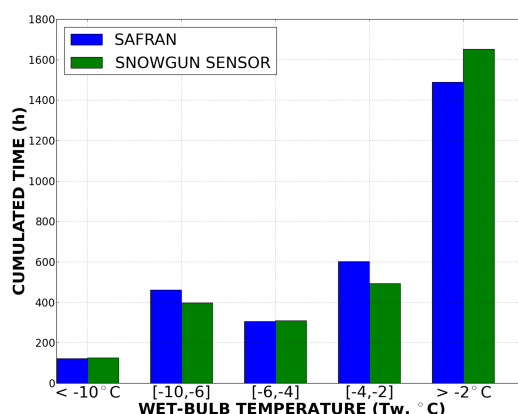


FIGURE 5.4 – Cumulated time-span over which wet-bulb temperature fell within specific ranges, from the in-situ data (snowgun sensor) and SAFRAN (20 November 2015 - 15 March 2016)

Snowmaking data

The production period was divided in the model into three distinct periods : before and after the resort opened (5 December 2015) and after 1 February 2016, the reasons being that the average conditions significantly differ (Table 5.7) and the ski slope surface opened to skiers was significantly enlarged as the season progressed, modifying the usable surface of the ski slope.

As a result, we used the water flow recorded by snowmakers and the observed ski slope surface area (Table 5.7) to force the MM snow precipitation rate in the model which is constant for each period (expressed in kg m⁻² s⁻¹). The daily production time was set in the model to match the observed daily production (expressed in kg m⁻², Figure 5.2). A wet-bulb temperature threshold of -3.5°C was found to be the minimum temperature for the triggering of snowmaking which afforded the production of the observed amount of MM snow during the first period (21 November - 05 December). Afterwards, the observed MM snow production could be simulated using a triggering temperature of -5°C.

Period	Total volume (m ³)	Average Water flow (m ³ h ⁻¹)	Average T _w (°C)	Production Surface (m ²)	MM Snow Precipitation rate (kg m ⁻² s ⁻¹)	T _w threshold (°C)
21 Nov. - 05 Dec.	1629	16.2	- 9.5	4063	1.11 10 ⁻³	-3.5
05 Dec. - 01 Feb.	657	10.2	- 6.7	6632	4.27 10 ⁻⁴	-5
01 Feb. - 01 Apr.	661	11.1	- 6.9	7067	4.36 10 ⁻⁴	-5

TABLE 5.7 – Observed production conditions for the main periods of production before and after the resort opened.

Observations and modelling of the seasonal snow accumulation

The variability of the snow depth (Figure 5.5) and thus of the associated snow water equivalent (SWE) on the ski slope was significant. The variability (standard deviation) of the SWE values in the study area showed a factor from 3 to 4 with the uncertainty σ_{SWE} (Section 5.2.3, Table 5.8). Two major observations can be made from the distribution of the snow depth on the ski slope (Figure 5.5) :

- the shape of the MM snow piles was not completely erased by the grooming machines. The maximum values of snow depth surrounded the center of the MM snow piles in December and January and was slightly further in April. This may be due to the slow erosion of the snow towards the bottom of the slope by skiers, despite the work made by the grooming machines.
- the initial distribution of the MM snow on the “useful area” defined on 4 December 2015 could still be noticed on the two latest dates (e.g. the northern and southern edge).

Date of observation	Snow Water Equivalent (kg m ⁻²)		
	Average SWE _{av}	Spatial Variability (Standard dev.)	Uncertainty σ_{SWE}
2015-12-04	278	87	28
2016-01-20	393	111	35
2016-04-06	501	120	33

TABLE 5.8 – The average SWE observed on the ski slope (SWE_{av}) along with the standard deviation of the raster values within the study area (Figure 5.5) and the uncertainty (σ_{SWE}) resulting from the computation in Section 5.2.3.

The average SWE difference between the simulation accounting for MM snow and the observations was 172 kg m⁻² (RMSD = 204 kg m⁻²) whilst between the simulation of groomed snow (no production) and the observations the average difference was - 239 kg m⁻² (RMSD = 282 kg m⁻²). On the three observation dates, neither of the two simulations provided conditions (SD, SWE) within the range of uncertainty of observations. Even though accounting for MM snow production significantly improved the simulation, the differences with observations remained high and suggested the actual amount of MM snow stood between these two simulations.

Based on the observations and the simulations of the natural and groomed snowpacks, we calculated the number of days when the snowpack equivalent water mass exceeded thresholds of 1 kg m⁻² and 80 kg m⁻² i.e. respectively the number of days with snow on the ground (Töglhofer et al., 2011) and with suitable conditions for skiing (a minimum of 20 cm of snow with a density of 400 kg m⁻³, Marke et al. (2014)). The following number of days were calculated :

- Concerning the natural snow, the ground was covered by snow for 107 days and the SWE exceeded 80 kg m^{-2} for 48 days of the season,
- Concerning the groomed snowpack (no production), the ground was covered by snow for 133 days and the SWE exceeded 80 kg m^{-2} for 82 days of the season,
- Concerning the ski slope (grooming plus snowmaking), the ground was covered by snow for 165 days and the SWE exceeded 80 kg m^{-2} for 159 days of the season (estimated from the observed melt-out date and the melting rate between 6 April and 3 May 2016).

In Les 2 Alpes ski resort, the ski season lasted from 5 December 2015 until 30 April 2016 i.e. 148 days. The days when the ground was covered by either natural or groomed snow were not consecutive : the snow melted entirely in late December and there was no snow during the Christmas holidays in both cases. Even though grooming significantly lengthened the snow cover period, the length of the season with suitable skiing conditions was far shorter than the period open to skiers (82 instead of 148 days). The production of MM snow therefore achieved the objective for the provision of consecutive days with snow on the ground, ensuring suitable conditions for skiing during the Christmas holidays and a sufficiently long skiing season.

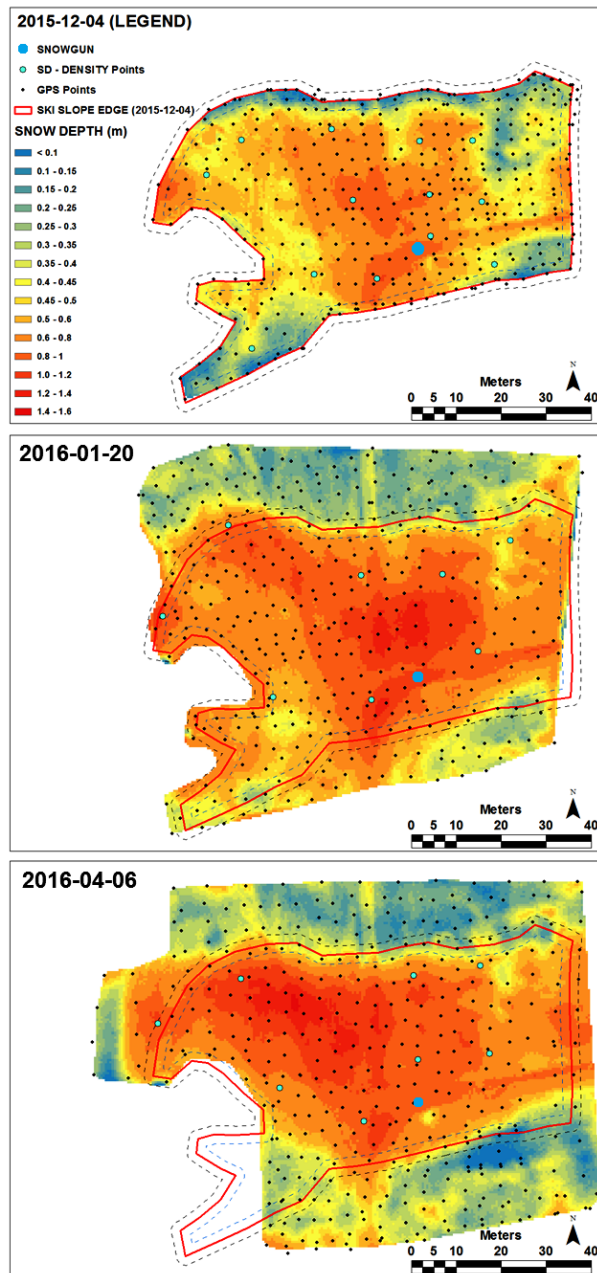


FIGURE 5.5 – Snow depth mapping for the three observation dates 2015-12-04 (top), 2016-01-20 (center) and 2016-04-06 (bottom). See Appendix 5.6 for details on the location of the observation site.

5.3.3 Water recovery rate from observations and simulations of the seasonal snow accumulation

The MM snow mass was calculated as the difference between the observed total mass of snow within the edge of the ski slope and the mass of natural snow from the simulated groomed snowpack (Section 5.3.2). The MM snow mass was further divided by the cumulated mass of water used for MM snow production up until the date of observations (Figure 5.2, Table 5.7), providing the water recovery rate (Table 5.9). Note that this calculation is based on each date on the total surface of the marked ski slope. This means that a significant part of the early production (before 5 December 2015) may have

fallen beyond the edge of the ski slope when opened to skiers on 4 December 2015 but within the edge of the ski slope when opened to skiers on 20 January 2016 (or 6 April 2016). This may partially explain the higher recovery rate on 20 January and 6 April 2016 compared to 4 December 2015 (Table 5.9).

Date	Ski slope surface (m ²)	Cumulated water mass for production (kg)	Observed mass difference (kg)	Water recovery rate (%)
2015-12-04	4063	1629 10 ³	974 10 ³ (± 167 10 ³)	59.8 (± 10.2)
2016-01-20	6632	2286 10 ³	1551 10 ³ (± 306 10 ³)	67.9 (± 13.4)
2016-04-06	7067	2947 10 ³	1896 10 ³ (± 315 10 ³)	64.3 (± 10.7)

TABLE 5.9 – Water recovery rate (**Average value** ± σ) from observations of the snow mass difference between ski slope snow conditions and simulated groomed snowpack conditions (i.e. without snowmaking).

Considering the first period of production (20 November - 5 December 2015), the simulations provided conditions within the range of uncertainty of the observation for water recovery rates of 65, 60 (minimum RMS of differences) and 55% (Table 5.10). From this initial step providing three potential snowpack conditions on 5 December 2015 (Figure 5.6), we performed twelve simulations across the second period of the season (after 5 December 2015) using four distinct water recovery rates of 100, 65, 55 and 45%. Of these twelve simulations, three provided results within the range of uncertainty for all three dates of observations (n = 3, Table 5.10) along with the minimum RMS of differences on the SWE (10 to 20 kg m⁻²). Detailed results can be found in Table 5.10.

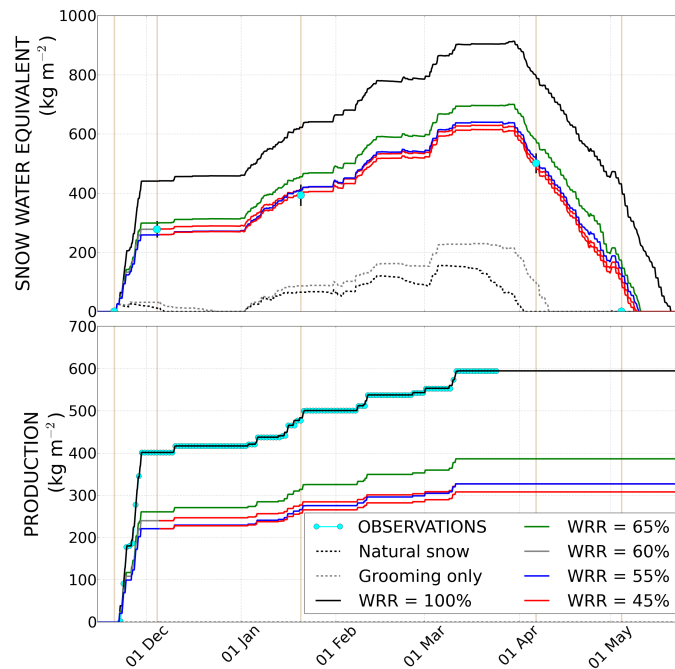


FIGURE 5.6 – Seasonal evolution of the ski slope snowpack. Simulations of natural snow and groomed natural snow conditions are shown along with simulations of the ski slope conditions including MM snow production, accounting for water recovery rates (WRR) of 100%, 65% and the three combinations (Table 5.10) which provided the best agreement with the observations (dots with error bars).

These results suggest that 55 to 65% of the total water mass used for production can be recovered as MM snow within the edge of the ski slope during the first period. This is consistent with the water recovery rates calculated in Section 5.3.1. The sensitivity test on the water recovery rate did not show any significant difference between the first period of production compared to later in the season. The water recovery rate may even be slightly lower with 45 to 55% of the SWE observed on the ski slope.

The season duration was computed from simulations similar to Section 5.3.2 for the three combinations of water recovery rates providing the best agreement with observations (Table 5.10). The ground was covered by snow for 170 to 171 days and the SWE exceeded 80 kg m^{-2} for 164 to 166 days during the season, which is consistent with the observed lengths (Section 5.3.2). The bias on the ski season duration and total melt-out date is attributed to a lower melting rate in the snow model compared to observations : an average - 15.8 to - $16.2 \text{ kg m}^{-2} \text{ day}^{-1}$ for the simulations using the three combinations of water recovery rates (Table 5.10) with respect to - $17.8 \text{ kg m}^{-2} \text{ day}^{-1}$ for the observations from 1 April 2016 to the total melt-out date.

Water Recovery Rate		n	RMS Difference			Melt-out date
Period 1	Periods 2 and 3		SWE (kg m ⁻²)	SD (m)	Density (kg m ⁻³)	
OBSERVATIONS		N = 3 observations			2016-05-03	
0%	0%	0	282	0.5	189	2016-04-10
100%	100%	0	204	0.28	50	2016-05-15
65%	65%	1	51	0.03	51	2016-05-10
60%	45%	3	9	0.05	63	2016-05-09
55%	55%	3	15	0.04	54	2016-05-09
55%	45%	3	11	0.07	62	2016-05-08

TABLE 5.10 – Performance of the snowpack model in simulating ski slope snow conditions. n is defined as the number of simulations found within the range of uncertainty for the observation dates. The RMS of the differences between the simulations and the observations are detailed for the 100% and 65% water recovery rate (WRR) simulations, for the three combinations of WRR which provided the best agreement with the observations (Figure 5.6) and for the simulation of the groomed snowpack (no production, WRR = 0%). Period 1 extends from 20 November until 5 December 2015. Period 2 and 3 extend from 5 December 2015 until the melt-out date.

The interest in both the professional (technical issues, investments) and research (climate change investigations) approaches of the production of snow lies in the consideration of the amount of “useful” additional MM snow that can be used on the ski slope. Any difference between the mass of water used for production and the additional snow mass on the ski slope can be considered as water loss in the mass balance. Such losses may be due either to the evaporation and sublimation of water droplets or snow particles (thermodynamic effects). They may also be due to the produced snow falling beyond the edge of the ski slope (mechanical effects). We intend in the following sections to address the impacts of such effects.

5.4 Discussions

5.4.1 Water losses due to thermodynamic effects (evaporation and sublimation)

Losses related to evaporation and sublimation can be calculated for the sake of the present study thanks to the linear relationship proposed by Eisel et al. (1988). Although significant changes in snow-guns technology have occurred in the last 30 years, this work remains at present the most detailed on this topic to the best of our knowledge. We might also consider this approach as a “worst case” scenario since the technological evolution has presumably evolved positively since, for better efficiency. The observed average temperatures of production were respectively - 9.5°C, - 6.7°C and - 6.9°C for the first, second and third periods of production (Table 5.7), resulting in respectively 5.84%, 7.9%, 7.7% water losses due to water vapor evaporation from droplets and sublimation of ice particles, both during and after their deposition on the ground (Eisel et al., 1988). The overall water loss over the total 2947 m³ used for snowmaking would be 6.7 ± 3% (Eisel et al., 1988), i.e. well below the observed differences in the present study. Evaporation and sublimation processes may explain to some extent the differences reported by either Eisel et al. (1990), Olefs et al. (2010), Spandre et al. (2016c) or those observed in

the present study. An overall water loss of 40% ($\pm 10\%$) was observed and simulated, in which less than 10% may be due to thermodynamic effects according to Eisel et al. (1988). This results in an additional mechanical water loss of approximately 30% of the total water mass used for MM snow production. The influence of external factors (topography, wind) proves a major concern for water loss.

5.4.2 Water losses due to mechanical effects

Although the wind conditions were ideal, a significant amount of snow was found at the toe or even at the back of the snowgun (Section 5.3.1). Wind drift of already deposited MM snow was very unlikely due to both the density and the cohesion of snow grains (capillarity/refrozen water). Since snowguns are usually installed on one side of the ski slope, a part of the production may fall outside the slope, behind the snowgun. The MM snow may also fall beyond the edge of the slope on the opposite side of the snowgun. Hanzer et al. (2014) performed a detailed study of technical snow in an Austrian ski area with 37 km of ski slopes for a total surface of 92 ha i.e. average ski slopes of 25m in width. Spandre et al. (2016a) reported similar data from a survey of French ski resorts with average ski slope widths of 20 m. The width of a ski slope may have a significant impact on the amount of MM snow falling within the edge of the ski slope in terms of the equivalent water masses of MM snow piles within 10 to 20 m from the center point (Table 5.4). These results also suggest that the best position of a snowgun is, if possible, in the middle of the ski slope (as is already the case in certain situations).

The surroundings of the ski slope are very important for the computing of the amount of “useful” MM snow. If the slope can be enlarged (as is the case for Les 2 Alpes Coolidge slope), the MM snow falling outside the initial edge of the ski slope can either be displaced by grooming machines or used for the extension of the slope. In the opposite case where the surroundings have complex topography (e.g. rough surfaces, with rocks) or are covered by vegetation (trees), the amount of snow falling beyond the edge of the ski slope is definitively lost. Consequently the potential for the extension of a ski slope is a significant factor for differences in MM snow efficiency between slopes (or even resorts). As a focus for this point, the study site may not be representative of the majority of ski slopes. The Coolidge slope is wider (it has a minimum width of 45 m, and a maximum of 75 m) than the ski slopes with average dimensions that have been referred to (Hanzer et al., 2014; Spandre et al., 2016a). This makes it a favourable site for the efficiency of MM snow : a maximum amount of the produced snow can be found within the edge of the slope. The total mass of water used for MM snow production also exceeds usual amounts : Spandre et al. (2016a) found that the usual capacity of water reservoirs was 150 to 190 kg of water per m^2 for an equipped ski slope with snowmaking facilities with a maximum of 390 kg m^{-2} . In the present case, 2947 m^3 of water were used for snowmaking (Table 5.7) across a maximum ski slope surface of 7067 m^2 (Section 5.2.1) i.e. 417 kg m^{-2} .

The influence of meteorological conditions on the efficiency of MM snow remains unknown to a great extent and requires further observation in order to be analysed, in light of the findings from Eisel et al. (1988). Meteorological conditions observed in this study appeared ideal for the production of MM snow : low wind speed and temperatures (Table 5.4). Such investigations may prove useful for operational purposes in providing objective data on the impact of producing snow in extreme conditions of wind or temperature.

The “Quality” parameter of MM snow chosen by professional snowmakers may also have a significant impact on the water recovery rate (Tables 5.4 and 5.5, Figure 5.3). The sessions concerning 21 January 2016 and 1 December 2015 differ mainly due to the parameterization of the “Quality” with significant differences in the WRR. To the best of our knowledge this parameter acts on the volume of compressed

air versus water volumes within the cloud expelled by the snowgun. There are objective reasons why this parameter has a significant impact on the water recovery rate. Higher air/water ratio leads to a lower specific humidity in the cloud of droplets and thus a lower gradient with the surrounding ambient air. This likely leads to decreasing latent heat exchanges (evaporation and sublimation) and increasing sensible heat transfer i.e. further freezing due to a higher surface for heat transfer between liquid water and air. Lastly, a lower water flow means a lower speed for droplets when they are expelled by the snowgun. There is then a higher probability that they fall within the edge of the ski slope. To provide an example, on 28 November 2015 the water mass used for production was $275 \cdot 10^3$ kg, leading to $159 \cdot 10^3$ kg of snow (WRR = 53%, Tables 5.4 and 5.5). On 21 January 2016, the water mass was $152 \cdot 10^3$ kg whilst the snow mass was $135 \cdot 10^3$ kg (WRR = 89%). The water mass used on 28 November 2015 was 1.8 times higher than that of 21 January 2016 which had only 1.08 times more in terms of snow mass. Further investigations are required to improve our understanding of the impact of this parameter and to confirm its influence.

5.4.3 Limitations of this work : assessment of water recovery rates and current modelling of ski slope snowpacks

The MM snow mass within the edge of the ski slope was computed from observations (Sections 5.3.2 and 5.3.3) or simulations (Section 5.3.3) and compared with the recorded mass of water used for production. These computations provided consistent values of the water recovery rate for the first period of production (before 5 December 2015) with 60% of the total water mass used for production within the edge of the ski slope open to skiers. Afterwards, the observations of the total mass of snow showed a higher WRR when accounting for the total surface of the ski slope (Section 5.3.3) compared with calculations with the surface limited to the edge of the ski slope on 4 December 2015 (Section 5.3.3). This suggests that a part of the initial production may have fallen beyond the initial edge of the ski slope. This higher WRR could also be due to an improved recovery of individual productions after 5 December 2015 as suggested by the observations on the MM snow pile on 21 January 2016. Simulations performed from the initial conditions of the snowpack on 4 December 2015 suggest however that the WRR is lower for the subsequent period than for the first. Several factors may explain these differences in the WRR. They could either be related both to objective factors not accounted for and to some weaknesses of the method. We intend hereafter to address such factors :

- The representativity of observations may be questioned. The observations of MM snow piles (Section 5.3.1) covered 75% of the total mass of water used for production during the first period (1214 out of 1629 m^3) while they covered only 11% of the production after 5 December 2015 (152 out of 1318 m^3). The observation on 21 January 2016 may not be representative of the whole period of production after 4 December 2015.
- The difficulty in monitoring human action on the ski slope (e.g. snow displacement by grooming machines) is a potential source of error. The distribution of snow on 6 April 2016 (Figure 5.5) suggests that there was a significant volume of snow displaced from the study area (within the 4 December 2015 edge) to the North-West corner of the ski slope (6 April 2016). Such displacements of snow may explain why the observed snow mass within the initial edge (4 December 2015) did not increase in the second period of production as we expected from initial snow conditions and further MM snow productions (after 4 December 2015).
- Thirdly, the snowpack evolution highlights strong non-linear thermal behavior (Armstrong and Brun, 2008) the effect of which might be significant for this study. In one case the natural and

groomed snowpacks in December completely melted, in the other the simulations accounting for the production of MM snow did not show a significant loss of equivalent water mass within the same period (Figure 5.6). Consequently, the SWE of the groomed snowpack on 4 December 2015 might not be lost on the ski slope and should be subtracted when calculating the mass of MM snow (Section 5.3.3). If accounting for an additional 20 kg m^{-2} equivalent water mass on the 4 December 2015 snowpack, we obtain adjusted water recovery rates of respectively 62.1% and 59.5% for 20 January and 6 April 2016. These corrected WRR are closer to those computed for the first period (59.8%, Section 5.3.3) and would tend to confirm that there is no significant difference in the WRR between the first and the two latest periods of production.

- Lastly, complementary observations might have reduced the uncertainty across estimations of the equivalent water recovery rate (an observation was performed on 2 March 2016 but could not be treated due to a GPS failure lasting until early April). Since the calculation of the mass of MM snow (Section 5.3.3) depends on the snow water equivalent of the groomed snowpack, observations on ski slopes without production would have been of great help. Every slope in study site surroundings is, however, equipped with MM snow facilities or is under the influence of these facilities. Extra observations on MM snow piles after 5 December 2015 could have clarified whether or not the higher WRR observed on 21 January 2016 was representative of the period or not. Additional observations with different types of snowguns would also have been of interest, although the snowgun used at the observations site is the most sold air/water gun of a brand which manufactures approximately 80% of the snowmaking facilities in French ski resorts (communication from the manufacturer). It may therefore be considered as representative of the current technology.

One dimensional (z-vertical) models feature several limitations for the simulation of ski slope conditions. These are highlighted in the present study through the bias on the total melt-out date related to lower melting rates of the simulations with respect to the observations.

- Firstly, the model can not account for snow / ground partitioning. The variability of the snow depth on the ski slope (Figure 5.6, Section 5.3.2) showed there were horizontal heterogeneities of snow properties, either due to the mass transport by skiers or the partial spreading of MM snow piles by grooming engines. This is particularly obvious when the total melting of the natural (and even groomed) snowpack in December and April made the ski slope an isolated snow patch in a mostly snow-free area with strong edge-effects. In such a situation the energy balance of the snowpack can be significantly affected by the modification of turbulent fluxes (Essery et al., 2006) and horizontal ground fluxes from snow-free areas in the vicinity (Lejeune et al., 2007). Since snow free areas have lower albedo values than the snow and are not limited to a 0°C maximum temperature, they can become significantly warmer than the surrounding snow and advect heat to the snow through the air (and respectively the ground), providing additional sensible heat energy to the snowpack. These two effects of the snow ground partitioning would enhance the melting rate in the model if they were accounted for, which is not the case.
- Secondly, the initial content of impurities in MM snow may also differ from natural snow. The amount of impurities in a snow layer is based on Crocus in both an initial value of impurities (i.e. initial albedo) and a deposition rate of dry impurities on the snowpack (Brun et al., 1992). There is no reason for the dry deposition to show a difference between natural snow and the snow on ski slopes (at the same location). The initial amount of impurities in MM snow could differ however from that in natural snow : the water used for production is stored in open reservoirs and probably contains more impurities than snow can capture in the air during growth and precipitation. This

could be a reason for a lower albedo of MM snow which would also enhance the melting rate on ski slopes.

5.5 Conclusions

The present study carried out detailed observations and simulations of snowmaking events and of the seasonal snow evolution of a ski slope snowpack in Les Deux Alpes ski resort (French Alps). The production of MM snow concentrated on the early season with approximately 50% of the seasonal production realized within one week in late November (Figure 5.6). The production of MM snow significantly improved the possibility of skiing at the observation site with suitable conditions from the opening (5 December 2015) to the closing date of the resort (30 April 2016).

We provided spatial observations of the snow depth and snow water equivalent of MM snow piles and of the ski slope once it was opened to skiers. A high spatial resolution of the snow surface elevation was used (0.5 m grid) thanks to measurements by a Differential GPS method. The related uncertainties were computed with a final uncertainty of 0.042 m on snow depth. The density of snow was measured thanks to snow sampling and weighting, with uncertainties ranging between 4 and 7% (Section 5.2).

The mass balance between the MM snow mass and the water mass used for snowmaking was defined as the water recovery rate. The observations of snowmaking events showed similar distributions around the center of the MM snow pile with approximately 30% WRR within 10 m and 50% within 20 m for production sessions in the early season (Section 5.3.1). The water recovery rate within the ski slope edge was computed on three occasions with approximately 60% ($\pm 10\%$) of the water mass used for snowmaking recovered as MM snow (Sections 5.3.2 and 5.3.2). The WRR was found to be relatively constant between observations and simulations and between the different periods of the season. The water losses due to thermodynamic effects were calculated from Eisel et al. (1988) linear approximation with less than 10% of the total water mass either evaporated or sublimated (Section 5.4). Over 30% of the water used for snowmaking probably turned to MM snow therefore, but could not be recovered within the edge of the ski slope, certainly due to mechanical effects (suspension and erosion by the wind, obstacles, etc) while production conditions can be considered as ideal (low wind speed and temperatures, large ski slope).

The water recovery rate of the snowmaking process poses therefore a tricky question regarding its likely dependence to both sites' characteristics (topography, vegetation) and human decision (attention to marginal conditions, quality parameter, etc.). Estimating a single value appears to be impossible even though the best conditions together (as can be considered in the present study) showed that a significant fraction of the water used for production was lost for the ski slope. The water recovery rate would have an optimum value when the most favorable conditions occurred together. An objective one is definitely the local topography : less than 50% of the water mass can be expected within the edge of a typical ski slope width (approximately 20 to 30 m, Section 5.4.2) with snowguns on the side and perpendicular to the slope (a typical installation). The authors also hypothesize that the wind may have a strong impact on the distances covered by water droplets and ice particles as well as the quality parameter chosen by professional snowmakers (although further investigation of such influences is needed).

Characterizing the actual mass of MM snow that can be recovered on ski slopes from a given mass of water remains a major issue for ski resorts regarding the current development of snowmaking facilities (Spandre et al., 2015) and the related costs of investments and production (Damm et al., 2014). Significant water losses may question the economical interest of snowmaking for resorts where

periods with suitable meteorological conditions are limited in addition to deteriorating factors for the efficiency of MM snow (obstacles e.g. trees, wind).

5.6 Spatial distribution of machine made snow properties with respect to the snowgun (Complementary material)

Brief introduction The parameterization of MM snow properties in Crocus - resort (density, specific surface area, sphericity) was compared to snow properties observations in several occasions (Chapter 4) confirming its consistency although highlighting a significant variability of MM snow initial properties within single sessions of production. Such variability was assumed to be related to a differentiated spatial distribution of the MM snow particles around the snowgun with respect to their properties. To the best of our knowledge there is no publication describing such phenomenon. We therefore aimed to introduce in the present section some complementary observations we realized on MM snow piles prior to snow volume measurements for most sessions of the 2015 - 2016 campaign in Les Deux Alpes ski resort of snow density, liquid water content and SSA, thanks to the DUFISSS instrument (Gallet et al., 2009). These measurements were performed over four sessions of the present study (24, 27 and 28 November 2015 and 21 January 2016) with 21 observations all together. The snow density, SSA and liquid water content were measured on each point. The position and elevation of observations points were observed thanks to the differential GPS and the snow depth was computed. The distance of observations points to the base of the snowgun was calculated with respect to the water flow direction i.e. with a positive sign when ahead of the snowgun, otherwise negative. The MM snow density (kg m^{-3}) and SSA ($\text{m}^2 \text{kg}^{-1}$) along with the inverse of the snow depth (m^{-1}) were plotted versus the distance (m) to the snowgun (Figure 5.7).

Results A significant amount of MM snow was found at the base or even at the back of the snowgun with usual values of 0.15 to 0.2 m thick MM snow layer at the base and 0.1 m at a 5 m distance behind the snowgun. The distribution of the MM snow showed a symmetrical parabolic shape around the center of the pile (dashed curves for single sessions, bold curve for all points together). The variability (standard deviation) of the snow depth was 0.15 m with a Root Mean Square (RMS) of differences between the quadratic model of the inverse of the snow depth (bold curve) with the observations corresponding to a 0.13 m snow depth. The model reached a minimum (maximum snow depth) for a distance of 11.3 m from the base of the snowgun.

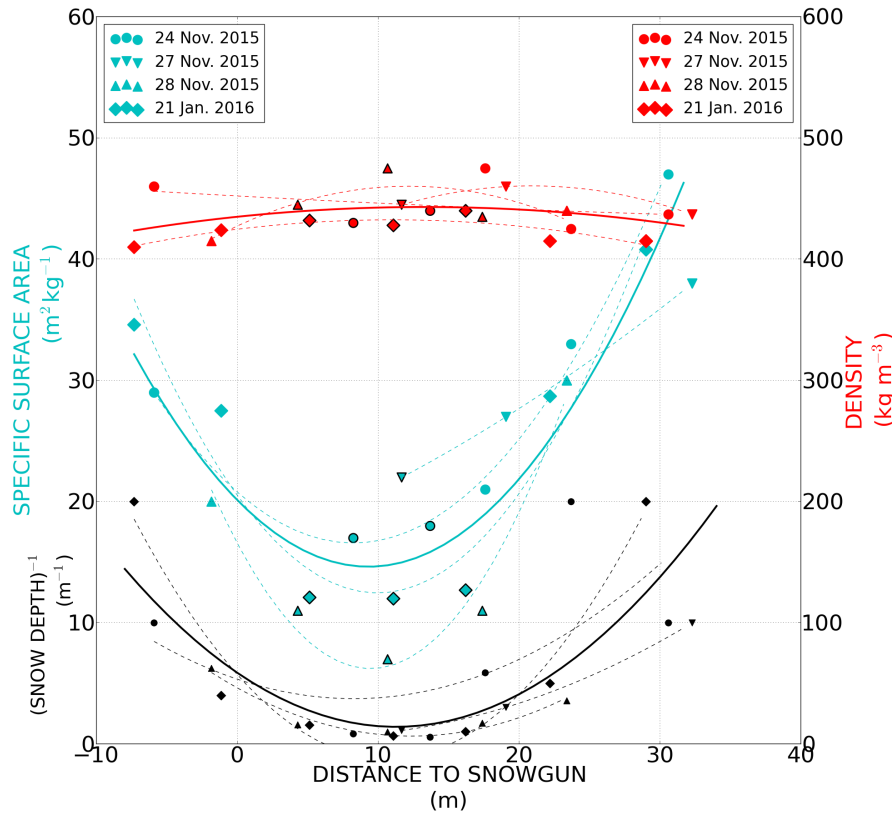


FIGURE 5.7 – Observed Machine Made snow properties (specific surface area, density) with respect to the distance to the snowgun in four occasions during the 2015 - 2016 winter season on MM snow piles prior to any action by grooming machines. Points where liquid water content was measured are circled with black edge.

The average specific surface area was $23.8 \text{ m}^2 \text{ kg}^{-1}$ (standard deviation $10.8 \text{ m}^2 \text{ kg}^{-1}$). The SSA showed a very similar quadratic evolution with respect to the distance to the base of the snowgun. Compared to a constant approach of SSA versus the distance to the snowgun (i.e. the average of values), the quadratic model significantly improved the RMS of differences ($4.9 \text{ m}^2 \text{ kg}^{-1}$, 21 observations), reaching a minimum SSA of $14.6 \text{ m}^2 \text{ kg}^{-1}$ for a 9.4 m distance to the snowgun. The quadratic relationship of the Specific Surface Area of MM snow (SSA_{MM} , $\text{m}^2 \text{ kg}^{-1}$) with the distance (d , m) between the observation point and the base of the snowgun is the equation (5.6). The SSA of MM snow was significantly related to the liquid water content with an average value of $13.6 \text{ m}^2 \text{ kg}^{-1}$ ($\pm 4.3 \text{ m}^2 \text{ kg}^{-1}$) for the nine points where liquid water was observed (circled with black edge in Figure 5.7) and concentrated ahead of the snowgun from a few meters up to 18 m . The snow was dry beyond this distance and behind the snowgun (twelve points) with an average SSA of $31.4 \text{ m}^2 \text{ kg}^{-1}$ ($\pm 7.5 \text{ m}^2 \text{ kg}^{-1}$).

$$SSA_{MM} = 0.063d^2 - 1.18d + 20.1 \quad (5.6)$$

On the contrary to the SSA, the MM snow density showed a weak relationship with the distance to the base of the snowgun and with the liquid water content. The average density for the nine points

where liquid water was observed was 441 kg m^{-3} (standard deviation 13 kg m^{-3}) and 434 kg m^{-3} ($\pm 20 \text{ kg m}^{-3}$) for the twelve points where snow was dry. All density measurements together had an average 438 kg m^{-3} ($\pm 18 \text{ kg m}^{-3}$) which was hardly improved by a quadratic model, showing a RMS of differences of 17 kg m^{-3} . These results suggest there is no significant spatial pattern of the snow density and that the main differences may be attributed to a fraction of the water to remain liquid or to turn entirely into ice with associated distinct snow microstructures.

Appendix of chapter 5 : Detailed analysis of uncertainties

Situation of the observations site

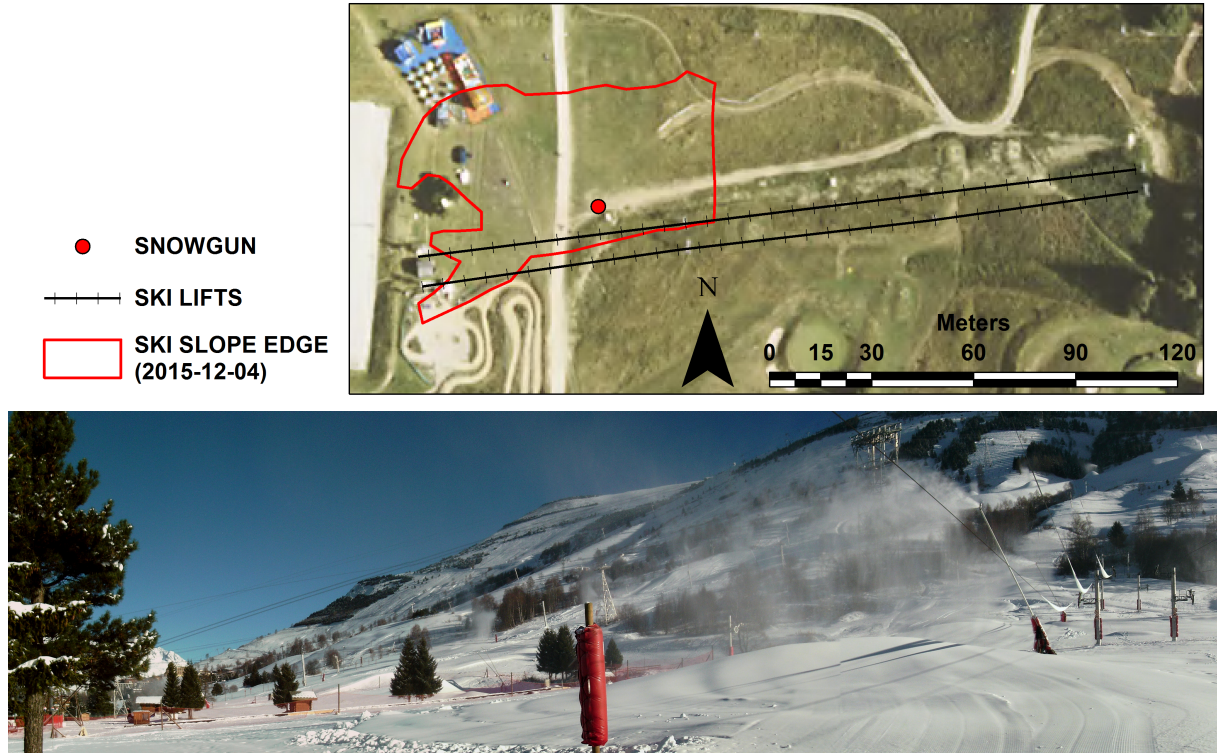


FIGURE 5.8 – (top) Observations site from above. Temporary structures in the top left corner were not present during the winter season.

(bottom) A picture of the production session on 27 November 2015. MM snow can be seen on the tree and on the cables of the ski lift.

Evaluation of uncertainties on snow depth

We used an Optech Iirris-LR laser scanner thewavelength of which (1064 nm) is adapted to the low reflectance of the snow in the infra-red spectrum. The laser scan point cloud was adjusted on targets the coordinates of which were determined thanks to a total station. The internal consistency of the target network was ± 0.0038 m and its relative positioning with respect to the GPS reference station was 0.008 m in planimetry and 0.013 m in elevation. We conducted Shapiro-Wilk tests for normality (Royston, 1982) over samples of 5000 differences between interpolated elevations and the TLS measurements (see below the average results). All tests suggest that the differences on snow surface elevation should not be considered as normally distributed even though the distribution is coherent with a normal distribution. (Figure 8a).

- Statistical value $w = 0.979$
- p-value = $1.48 \cdot 10^{-25}$ (< 0.05)

Secondly, we compared the interpolated snow-free surface elevations from the existing Digital Elevation Model of the ground. We conducted once more Shapiro-Wilk normality tests (Royston, 1982) over samples of 5000 differences between interpolated ground elevations and the Digital Elevation Model

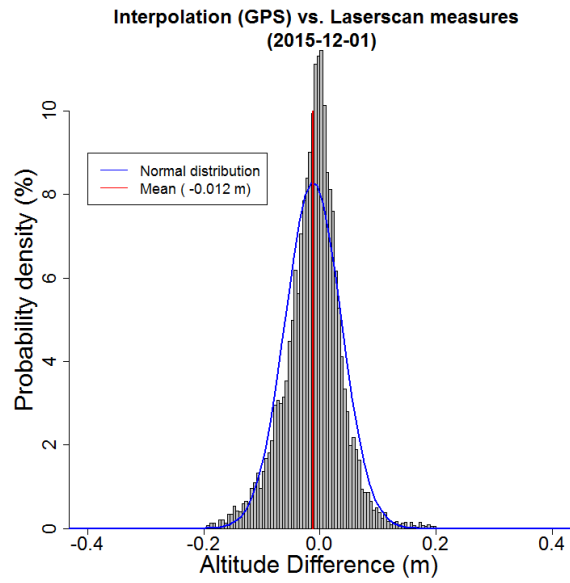


FIGURE 8a – Probability density of the elevation differences between the interpolated snow surface and the TLS snow surface on 1 December 2015

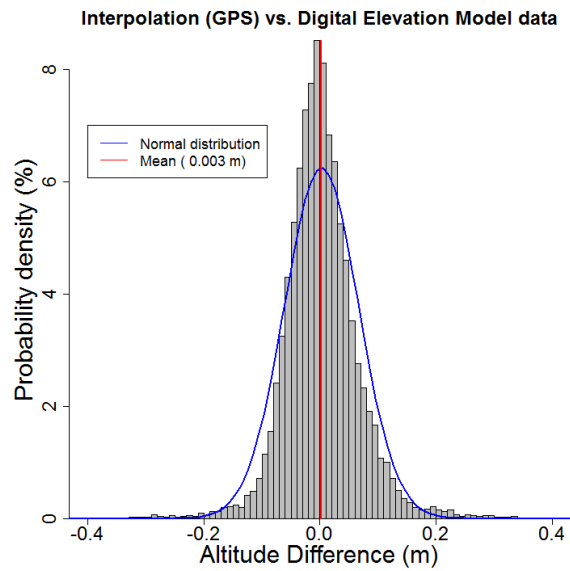


FIGURE 8b – Probability density of the elevation differences between the interpolated bare ground surface and the Digital Elevation Model ground surface

data (see below the average results). All tests suggest that the differences should not be considered as normally distributed even though the distribution appears to be very consistent with normality (Figure 8a).

- Statistical value $w = 0.951$
- p-value = $1.59 \cdot 10^{-34}$ (< 0.05)

Lastly, the GPS interpolated snow depth was compared with hand made measurements on several occasions (Table 5.2, Figure 5.9). We conducted a Shapiro-Wilk normality test (Royston, 1982) to ascertain the differences between interpolated snow depth and the manual measurements (see below). This suggests that the differences on snow depth are normally distributed :

- Statistical value $w = 0.963$
- p-value = 0.38 (> 0.05)

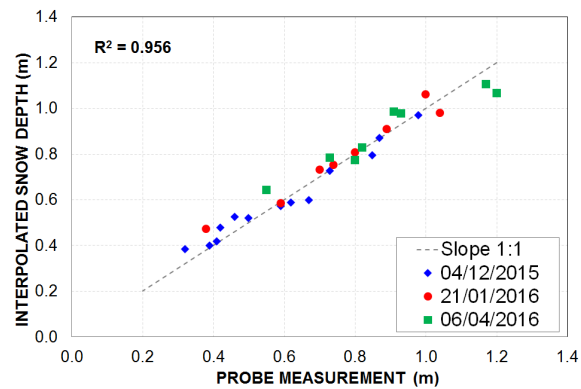


FIGURE 5.9 – Interpolated snow depth from GPS method with respect to the hand made probe measurements for each observations session of ski slope. Average difference and RMS of the differences are detailed in Table 5.2

Troisième partie

Dynamics and interactions of snow conditions with the industrial activity of ski resorts

Chapitre 6

Investigations on socio economic indicators of French Alps ski industry from an explicit spatial modelling of managed snow on ski slopes

This chapter corresponds to the paper by Pierre Spandre, Hugues François, Samuel Morin, Emmanuelle George-Marcelpoil and Matthieu Lafaysse “Investigations on socio economic indicators of French Alps ski industry from an explicit spatial modelling of managed snow on ski slopes”, submitted to Journal of Tourism Management

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6.1 Introduction

Winter tourism is a recent activity less than a century old which became a major industry in the French Alps after the 1950's and the deep changes in the social and economic structure of mountain areas (Marcelpoil et al., 2012; Lecuret et al., 2014). Beyond the structural inter-dependence of the construction of real estate and the ski lifts offer (Fablet, 2013), the consecutive seasons in the late 1980's with poor natural snow conditions (Durand et al., 2009b) revealed a major dependence of the ski industry to snow conditions (Koenig and Abegg, 1997). This raised the interest of policy makers and scientists in Europe and Northern America for investigations of the capacity of ski resorts to anticipate, cope with and recover from the impact of natural "hazards" in terms of lack of snow i.e. assessing the vulnerability of the ski industry to meteorological and snow conditions (Adger, 2006). Initial studies in the early 2000's defined this vulnerability of ski resorts based on a statement referred to as the "100 days" rule and later considered as the reference approach for investigations of climate induced impacts on the winter tourism (Koenig and Abegg, 1997; Elsasser et al., 2002; Abegg et al., 2007; Steiger, 2010; Pons-Pons et al., 2012; François et al., 2014). This rule states that a ski resort is snow reliable if the snow depth exceeds 30 cm during 100 days or more, featuring the capacity to provide objective information when comparing distinct periods (past and future) or locations (Koenig and Abegg, 1997; Elsasser et al., 2002; Abegg et al., 2007). Usual results are the length of the ski season at a given location and a binary assessment reliable / not reliable which often required additional processing to reveal socio-economic implications of computed changes (Scott et al., 2006; Pons-Pons et al., 2012; François et al., 2014). Further computations consisted in calculating the snowmaking requirements to compensate the loss in the ski season length (Scott et al., 2003, 2006; Steiger, 2010; Pons et al., 2015), in assessing the drop in skier days (i.e. ski lifts tickets sales) related to a shorter ski season (Pons-Pons et al., 2012), or in comparing the calculated length of the ski season with socio economic indicators such as the skier days (François et al., 2014). Subsequently some investigations revealed the interest for alternative indicators of snow conditions such as the use of snow mass instead of snow depth (Marke et al., 2014) or the number of days with snow on the ground (Töglhofer et al., 2011; Pickering et al., 2010) and the importance of specific periods for the economic success of a winter season (Scott et al., 2006; Falk and Hagsten, 2016). The "100 days" rule ignores such relative economic weight of specific periods, also failing to consider distinct snow requirements relatively to the period of the season (Hennessy et al., 2007; Steiger, 2010), or the differences between the natural snow properties and the Machine Made (MM, Fierz et al. (2009)) or even groomed snow (Guily, 1991; Fahey et al., 1999; Fauve et al., 2002). To the best of our knowledge, the snowmaking requirements computed thanks to the application of the "100 days" rule have been compared to records of water volumes used for snowmaking only once (Rixen et al., 2004) and the link between the obtained ski season length and actual annual skier days showed clear limitations (François et al., 2014). Overall, little investigation has been undertaken to evaluate the "100 days" rule as a relevant marker of the actual vulnerability of ski resorts to snow conditions in past decades (Rixen et al., 2004; Pons-Pons et al., 2012). Alternatively, the vulnerability was questioned in terms of skier days or overnight stays with respect to the snow conditions (Falk, 2010, 2014; Töglhofer et al., 2011) inadequate for investigations under projected climate conditions (IPCC, 2014; Gilaberte-Búrdalo et al., 2014) or potential evolutions of infrastructures e.g. snowmaking facilities (Spandre et al., 2015). Recently a significant effort was realized in this field to combine detailed and physically based snow models able to account for snow management (Hanzer et al., 2014; Howard and Stull, 2014; Spandre et al., 2016c) with relevant socio-economic variables for the operational activity of ski resorts (Damm et al., 2014; Scott and McBoyle, 2007; Spandre et al., 2016a) in order

to provide integrated modelling approaches for prospective investigations of climate change impacts on the ski industry (Scott et al., 2006; Dawson and Scott, 2013; Marke et al., 2014). Shortcomings still remain either in the snow modelling approach, often simplistic (Scott et al., 2006; Dawson and Scott, 2013; Hendrikx and Hreinsson, 2012), the relationships between snow related indicators and economic implications (Marke et al., 2014; Pons et al., 2015) or the potential of the methods to be transferred to other locations or time periods due to the large inputs requirements (Damm et al., 2014; Pons et al., 2014). This makes difficult to use these methods in other regions where large scale investigations of the vulnerability of the ski industry to the snow conditions have remained limited to the analysis of natural snow conditions by the “100 days” rule (e.g. French and Italian Alps), either under past or projected climate conditions (Abegg et al., 2007).

In the present study we introduce an innovative modelling approach of snow conditions in French ski resorts. In a first section we review the existing literature on this topic and the related limitations, particularly regarding the analysis of the French Alps ski resorts. In a second section, we describe our method which consists in the integration of a physically based snowpack model accounting for explicit snow management (Spandre et al., 2016c) with spatial representations of ski slopes for the French Alps ski resorts (François et al., 2014) including a new detailed approach of areas equipped with snowmaking facilities. Snow conditions were simulated over the 1958 - 2014¹ period with distinct scenarii of snowmaking infrastructures (0 to 45% of equipped surface with snowmaking facilities). Snow related viability indicators were defined and correlated to the recorded skier days over the 2001 - 2014 period (DSF, 2014) and compared with previous investigations based on natural snow (Abegg et al., 2007; François et al., 2014). The results provided by this modelling approach are detailed in a third section, including the computation from simulations of the aggregated water volumes and associated energy costs used for snowmaking and compared them to the available recorded data (Badré et al., 2009). The fourth section consists of a discussion of the major limitations and outlooks of the present work, particularly the capacity of this modelling chain to provide relevant information for prospective investigations of both the snow reliability of ski resorts and the evolution of snowmaking infrastructures (facilities, water and energy consumption).

6.2 Literature review

The Snow Reliability Line Koenig and Abegg (1997); Elsasser et al. (2002) in Switzerland and later Abegg et al. (2007) in the rest of the European Alps (Austria, Italy, Germany, Slovenia and France) defined the snow reliability line (SRL) as the elevation where the “100 days” rule requirements were fulfilled based on the natural snow conditions. The median elevation of every ski resort was computed as the average of the base and summit elevations of the resort and compared with the SRL elevation. The ski resort was declared snow reliable if its median elevation was higher than the SRL elevation, otherwise unreliable (Abegg et al., 2007). According to this analysis, 91% of the 666 ski resorts in the European Alps were snow reliable in 2005 (Abegg et al., 2007). Significant spatial variation of the SRL elevation was shown, ranging from 1050 to 1500 m.a.s.l with consequences on local reliability of ski resorts : in 2005, 69% of ski resorts were snow reliable in Germany and up to 97% in Switzerland and France. Abegg et al. (2007) computed the impact of climate change on the SRL elevation and concluded that under a +1°C warming compared to present, only 75% of European Alps ski resorts would remain reliable and respectively 61% and 30% for +2°C and +4°C warmings compared to present.

1. Winter seasons are referred to by the opening year i.e. “2001” for the “2001 - 2002” winter season. The 1958 - 2014 period therefore starts in August 1958 and ends in July 2015.

Steiger (2010) later showed the limitations of the snow reliability line approach by the analysis of 52 climate stations in Austria over the 1981 - 2001 period and concluded that an elevation of 1200 m.a.s.l could not be confirmed as snow reliable for all regions of Tyrol (Austria).

Snowmaking requirements Beyond this initial analysis of the snow reliability in the European Alps, further investigations questioned the importance of snowmaking as a relevant mitigation method against the natural variability and projected changes of the climate. Scott et al. (2003) developed a simple modelling approach calibrated on a 17 years long period in the Southern Ontario region (Canada). The average season duration was computed for the Horseshoe ski resort (case study) over the 1961 - 1990 baseline period based on climate thresholds (snow depth and air temperature). Scott et al. (2003) considered that a snow base depth of 50 cm was required for skiing activities and used this to drive snowmaking in the model. The method provided consistent season lengths for the baseline period which significantly decreased under projected climate conditions despite the increasing need for snowmaking. Scott et al. (2006) later used this modelling approach and a 60 cm snow base depth requirement in the Québec region (Canada) with similar results. Steiger and Mayer (2008) applied this method in Tyrol (Austria) to compute the elevation of the SRL when accounting for snowmaking, considering the elevation where the “100 days” rule was fulfilled for nine out of ten winter seasons. Based on the records of three climate stations Steiger and Mayer (2008) concluded that snowmaking could guarantee the snow reliability at elevations above 1000 m.a.s.l. for the 1971 - 2000 reference period. Steiger (2010) further developed the snowmaking approach by stating that a 30 cm “base layer” was produced in the early season regardless the snow conditions with further “improvement snowmaking” if required. Hanzer et al. (2014) later implemented a similar approach in a physically based snowpack model. Based on the methodology by Scott et al. (2003), Steiger (2010) concluded that snowmaking would remain a suitable mitigation method until the 2050's with a significant increase of water and energy requirements. This approach (or similar developments) was further used to assess the impact of climate change on the ski season length and the snowmaking requirements to compensate the loss in the Southern Black Forest region of Germany (Schmidt et al. (2012), in three sites of Switzerland (Rixen et al., 2011), another three ski resorts of Andorra (Pons-Pons et al., 2012), 41 ski resorts in the Pyrenees (Pons et al., 2015), 103 ski resorts in the U.S.A Northeast region (Dawson and Scott, 2013), ten ski resorts in New-Zealand Hendrikx and Hreinsson (2012), nine alpine ski resorts in Australia (Hennessy et al., 2007; Pickering et al., 2010).

To the best of our knowledge, the evaluation of simulated water volumes requirements for snowmaking purposes and associated energy costs are limited to the study by Rixen et al. (2011) on the 2006 - 2007 winter season over two study sites in Eastern Switzerland. Hanzer et al. (2014) also compared the simulated water consumption with records of water volumes used for snowmaking although by means of a significantly different modelling approach based on the spatially distributed and physically based snowpack model AMUNDSEN (Strasser et al., 2008). A snowmaking module was coupled to the AMUNDSEN model to simulate the snow conditions in a ski area of the Schladming region (Austria) over the 2003 - 2011 period. The model provided consistent season length and water and energy consumption for snowmaking purposes with respect to the records provided by the ski resort. This modelling approach was certainly the most accomplished in 2015 and was further used for climate change impacts investigations (Damm et al., 2014). Marke et al. (2014) however revealed the main limitation of this method which is hardly transferable to other ski areas due to the significant inputs requirements, particularly regarding the geographical information on study sites.

Representation of ski slopes in ski resorts Breiling and Charamza (1999) proposed original indicators to analyse the snow conditions in Austria by considering the mean elevation of residential population defined as the elevation of the ski resort main places weighted by the surface areas and the mean elevation of starting points of ski lifts. Afterwards most investigations based on the “100 days” rule used single points representations of ski slopes to assess the snow and meteorological conditions of a given ski resort. The median elevation of each ski resort defined as the average of summit and base elevations was the reference approach (Abegg et al., 2007; Scott et al., 2003; Steiger, 2010; Dawson and Scott, 2013; Pons et al., 2015). Schmidt et al. (2012); Rixen et al. (2011) used the “highest”, “middle” and “lowest” elevations of the study area while Hennessy et al. (2007) mixed various approaches by considering either a single point or three distinct elevations for each ski resort. Scott et al. (2006); Hendrikx and Hreinsson (2012) selected the closest climate stations to the base elevation of the study areas arguing this was the most vulnerable portion. Alternatively, Pons-Pons et al. (2012) considered the lowest and highest elevations in which 75% of the ski slopes surface area was concentrated and Falk and Vanat (2016) the mean elevation of ski lifts weighted by their transport capacity. These remain coarse representations of ski slopes which may highly underestimate the spatial variability of snow conditions (?) and the associated uncertainty on the reliability assessment of a given ski resort. The most recent investigations accounted for spatial informations on ski slopes and simulated the snow conditions on the grid cells of a Digital Elevation Model of the ground provided by the ski resorts (Hanzer et al., 2014; Damm et al., 2014). François et al. (2014) built up spatial representations of ski slopes based on the ski lifts of French Alps ski resorts by means of a systematic approach, providing a skiable envelope including all ski slopes of a ski resort with detailed information (elevation, slope and aspect). Such representations of ski slopes show large potential for small scale investigations such as the spatial distribution of snowguns within ski resorts (Hanzer et al., 2014; Spandre et al., 2016a).

Economic implications Scott et al. (2006) first showed the limitations of the “100 days” rule as an economic indicator and proposed an additional approach by dividing the ski season into five segments. Scott et al. (2006) identified that three out of these five segments covered 89% of the seasonal skier days, with the Christmas and School holidays together concentrating 55% of skier days within only five weeks. Scott et al. (2006) concluded on the economic importance of specific periods which can not be revealed by the “100 days” rule. Damm et al. (2014) highlighted a similar distribution of the skier days in Austria. Pons-Pons et al. (2012) and Pons et al. (2014) related the reduction of the ski season length to a drop in skier days by means of an Agent Based Model (ABM) which was calibrated over the Pyrenees based on ski resorts statistics and survey data of tourism activity. François et al. (2014) defined a viability index of French Alps ski resort based on the natural snow conditions as the share of ski slopes of a resort encountering more than 30 cm of snow depth for 100 days or more over the entire winter season. This index aggregated for all French Alps ski resorts was significantly correlated to the recorded skier days over the 2001 - 2011 decade (correlation coefficient $R^2 = 0.86$) although failing to predict the magnitude of the impact of the snow conditions on the evolution of skier days (François et al., 2014). This indicator captures well the covariation of skier days and snow conditions although failing to predict the rate of variation. As an example the viability index computed for the 2010 - 2011 winter season showed a similar drop to the index computed for the 2006 - 2007 winter season although the drop in skier days was significantly different (François et al., 2014). Dawson and Scott (2013) used the methodology by Scott et al. (2003, 2006) in the U.S Northeast region based on the season length computed with the use of the “100 days” rule and on the probability of being operational during the Christmas and New - Year holidays (assuming a 75% probability could be considered as a threshold for

reliability). Dawson and Scott (2013) projected that 56 out of the 103 resorts (54%) would be able to maintain a 100 days ski season length over the 2010 - 2039 period under a high emissions scenario, and only 41 resorts (40%) would be considered as snow reliable when using the additional criteria on Christmas and New - Year holidays.

Economic implications can also be derived from the application of the “100 days” rule by calculating the costs related to the computed water and energy requirements either at present (Rixen et al., 2011) or under projected climate conditions (Pickering et al., 2010). The combination of lower revenues due to the shortening of the season and of higher charges related to increased snowmaking was used to infer an estimate of the total revenue reduction under projected climate conditions by Scott et al. (2006) in the Québec region (Canada), Dawson and Scott (2013) in the U.S Northeast or Pickering et al. (2010) in Australia. Scott et al. (2006) indicated that over the 1997 - 2004 period the operating profit margins for the Canadian ski industry had an average 13.9% and concluded that the expenses may exceed the revenues by the 2050's according to climate scenarios. The major threat of climate change on the ski industry may not be the technical possibility to produce snow but the unreliable economic situation of ski resorts which may do so (Scott et al., 2006; Scott and McBoyle, 2007; Pickering et al., 2010; Damm et al., 2014). This highlights the importance of investigations of economic implications of the natural variability and projected climate conditions impacts on the skier days (revenues) and water and energy requirements for snowmaking (costs), and therefore the need for means to do so.

In the present study we therefore introduce an innovative modelling approach of snow conditions and interactions with the economic activity in French ski resorts. The method we employed and indicators we computed are detailed in the next section.

6.3 Material and Methods

6.3.1 Study area and periods considered for the present study

Study area The French Alps represent the largest regional ski market in France with 141 out of the 220 French ski resorts (64%) located in the region, of which 106 (48%) are located in the Northern Alps (NA) and 35 (16%) in the Southern Alps (SA). According to the French national observatory of tourism activities (ODIT, 2009), 84% of the national ski lifts facilities are located in the French Alps (69% NA + 15% SA) along with 84% of the ski slopes surface areas (64% NA + 19% SA). The annual revenue of French ski lifts operators is in a large extent realized in the French Alps (89% , 78% NA + 11% SA) with 105 000 out of the 120 000 employment positions (88%, 75% NA + 13% SA) generated by the ski industry (DSF, 2014). Over the 2001 - 2014 period, France shared the top ranks of annual ski lifts tickets sales (skier days) with the U.S.A and Austria. France sold an average 53.9 millions tickets on this period (Abegg et al., 2007; DSF, 2014). The French national association of ski lifts operators (Domaines Skiabiles de France, DSF) divided the winter season into five segments showing steady revenue weights over this period of time (DSF, 2014). The segment between the opening of ski resorts and the end of Christmas and New-Year holidays covered 25 to 30% of ski lifts tickets sales and the February School break 30 to 35% of sales (DSF, 2014). A similar distribution of overnight stays was published by the observatory of Savoie Mont-Blanc² tourism with 19% of overnight stays in the early season and Christmas holidays and 33% during the February School break (Lecuret et al., 2014). Alpine skiing was confirmed as the major attraction of the French winter tourism with 70% of visitors that enjoy this activity (Lecuret et al., 2014).

2. French departments of Savoie (73) and Haute-Savoie (74)

Periods The national skier days provided by Domaines Skiabiles de France showed a statistically significant increase according to the Pearson product moment correlation test (Onwuegbuzie et al., 2007) for the 1990 - 2001 period ($R^2 = 0.69$, $p\text{-value} = 8.10^{-4}$) with an average rate of increase of 600 000 skier days per year. From 2001 onwards, the time evolution of skier days was not statistically significant ($R^2 = 0.16$, $p\text{-value} = 0.15$). We therefore distinguished three periods for the present study considering the total period when meteorological forcing data were available (1958 - 2014), the period from the first installation of snowmaking facilities in the French Alps (1985 - 2014) and the period since skier days showed a relatively steady value (2001 - 2014).

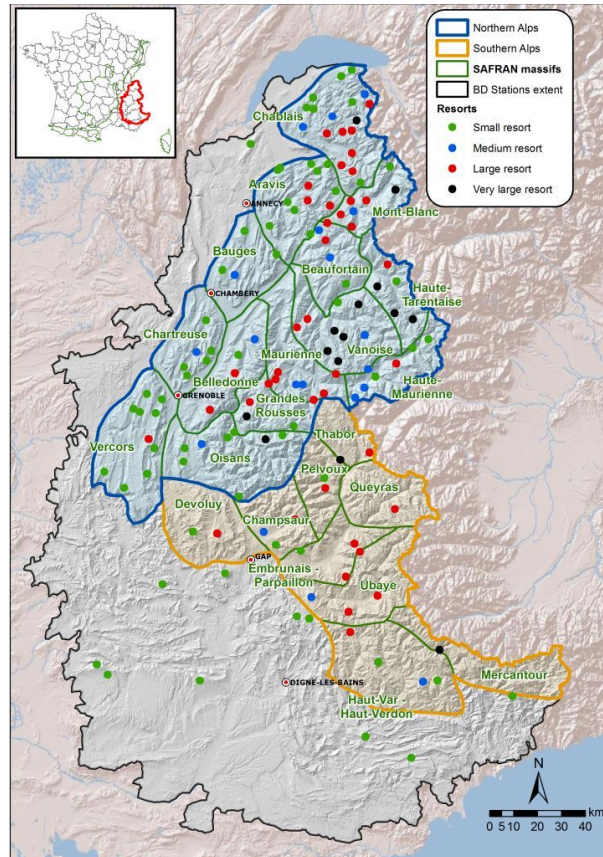


FIGURE 6.1 – The 23 alpine massifs from the SAFRAN meteorological system. Details on ski resorts covered by the present study can be found in François et al. (2014).

6.3.2 Modelling of snow conditions

SURFEX/ISBA-Crocus snowpack model The multilayer snowpack model SURFEX / ISBA-Crocus (thereafter Crocus, Brun et al. (1992); Vionnet et al. (2012)) explicitly solves the equations governing the energy and mass balance of the snowpack. This is done in a detailed manner which includes internal phenomena such as phase change, water percolation, snow compaction, snow metamorphism and information concerning their impact on the radiative and thermal properties of the snowpack. The energy budget of the snowpack is explicitly solved at its two interfaces (snow/atmosphere and snow/ground) and within the vertical profile. The snowpack is discretized with up to 50 numerical layers ensuring an appropriate description of the snowpack's internal processes.

Crocus Resort The “Crocus Resort” version of the model allows taking into account the effect of grooming and snowmaking on the snow properties (density, Specific Surface Area (SSA) and sphericity) to provide simulations of a ski slope snow conditions (Spandre et al., 2016c). The impacts of grooming are simulated as both a static weight on the snowpack and the effect of tilling on the snow : mixing and evolution of surface layers properties. Machine made snow can be added to the snowpack specifying the precipitation rate ($\text{kg m}^{-2} \text{s}^{-1}$), the initial snow properties (density, SSA and sphericity) and conditions for triggering the production (wet-bulb temperature threshold, target quantity or target snow depth or snow water equivalent, etc.). All simulations including snowmaking account for the impact of grooming. The parameterization of the snowpack model we used in the present study corresponds to the standard values from Spandre et al. (2016c) i.e. MM snow is set to rounded grains (SSA of $22 \text{ m}^2 \text{ kg}^{-1}$, 90% sphericity, 500 kg m^{-3} density) and the tilling effect progressively changes the SSA of snow to $25 \text{ m}^2 \text{ kg}^{-1}$ (unless lower), density to 450 kg m^{-3} and sphericity to 90% (both unless higher).

SAFRAN meteorological data The meteorological system SAFRAN (standing for “Système d’Analyse Fournissant des Renseignements Atmosphériques à la Neige”) provides meteorological data (temperature, precipitations, etc.) for mountain areas of an approximate 1000 km^2 surface referred to as “massif” (Figure 6.1). Within each massif, the meteorological conditions are supposed to be homogeneous and to depend only on the elevation (Durand et al., 1993). The altitudinal resolution is 300 m and the time step is 1 h. Please note the minimum and maximum elevations vary from a massif to another due to specific characteristics of massifs. SAFRAN merges numerical weather predictions model outputs (atmospheric profiles of temperature, humidity and wind speed), surface observations (automatic weather stations, manual observations) and radiosonde observations. Here we used the SAFRAN data from August 1958 to July 2015 (57 winter seasons). SAFRAN is based on global numerical weather predictions models reanalysis and observations which evolved since their creation, particularly from the 1980s which is a source of variability in time and space (Vidal et al., 2010). Despite these uncertainties, SAFRAN is a powerful tool for research purposes that has been extensively used to assess climate change impacts in French mountain regions (Martin et al., 1994; Gerbaux et al., 2005; Durand et al., 2009b; Lafaysse et al., 2011). Several research activities illustrated that the SAFRAN-Crocus model chain yields satisfactory results in French mountain regions (Durand et al., 2009b; Rousselot et al., 2010; Spandre et al., 2016c).

Technical snow production The production of MM snow was computed using literature values describing snowmaking practices in ski resorts (Hennessy et al., 2007; Steiger, 2010; Hanzer et al., 2014; Spandre et al., 2016a). The winter season was divided into periods with distinct rules for snowmaking :

- Between the 1 November and the 15 December a 30 cm deep “base layer” (150 kg m^{-2}) is produced, if meteorologically possible, regardless of the natural snowfalls during this period.
- Between the 15 December and the 28 February snow is produced, if meteorologically possible, to maintain a total snow depth of 60 cm.
- After the 1 March no more snow is produced.

In France, Spandre et al. (2016a) estimated an average 2.5 to 3.1 snowguns per hectare of ski slope equipped with snowmaking facilities. We therefore considered that every snowgun covered a 3500 m^2 surface with an average water flow of $15 \text{ m}^3 \text{ h}^{-1}$ (standard value), resulting in a MM snow precipitation rate of $1.2 \cdot 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$. The production of MM snow was possible from 6 p.m. until 8 a.m. the following morning (Spandre et al., 2016c) which makes a maximum quantity that can be produced within one day of 60 kg m^{-2} i.e. 12 cm of MM snow. This is consistent with assumptions from Scott

et al. (2003); Steiger (2010); Pons et al. (2015). The wet-bulb temperature thresholds we used to trigger snowmaking was -2°C i.e. the maximum temperature ensuring the technical feasibility of snowmaking (Olefs et al., 2010). A 4.2 m s^{-1} wind speed is the maximum value for the production of MM snow (Spandre et al., 2016c). Water losses during the snowmaking process (Eisel et al., 1988; Spandre et al., 2016b) are not taken into account in the present study.

6.3.3 Spatial and structural data on ski resorts

All data on the geographical location and structural data on ski resorts were extracted from the “BD Stations”³ database managed by Irstea (Marcelpoil et al., 2012). The “BD Stations” was created on request of the “Comité de Massif des Alpes” institutional committee to give access to a wide range of data and sources focused on ski resorts through a structured frame. These data cover administrative aspects (ski lifts are part of public services and under the responsibility of municipalities) as well as management aspects (the resort’s management can be handled by the municipality or transferred to semi-public or private companies). The BD Stations is a powerful tool to support investigations either focused on large territories where winter sports are an activity among many others or zoomed at the scale of a single ski-lift (François et al., 2014; Francois et al., 2016; Spandre et al., 2015).

Location and capacity of ski lifts Specific national laws apply to ski lifts in France which installation and operation are supervised by a national service (STRMTG, standing for “Services Techniques de Remontées Mécaniques et Transports Guidés”). The STRMTG administrates a dedicated database to ski lifts (CAIRN, “CAatalogue Informatisé des Remontées Mécaniques Nationales”) which includes technical characteristics of each ski lift such as the Ski Lift Power (SLP). The SLP is an indicator of the size of a ski lift, commonly employed by the French national association of ski resorts (DSF, standing for “Domaines Skiables de France”). The SLP is defined as the product of the elevation difference between the bottom and the top of a ski lift (in km) and its flow of persons per hour (pers h^{-1}), thus expressed in km pers h^{-1} , (DSF, 2014). Aggregated for each ski resort, it allows classifying them in four resorts types as described in Table 6.1, according to François et al. (2014). These data are completed with geographical information from the database BDTOPO (25 m of resolution) developed by the French Geographical Institute (IGN, “Institut Géographique National”).

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

TABLE 6.1 – Ski resorts categories regarding the ski lift power

Beyond the ski lift power, the features of ski resorts we refer to in the present study are also taken from the “BD Stations” database (Marcelpoil et al., 2012) :

- The ski lifts mean elevation is defined as the average of top and bottom elevations of each ski lift weighted by its SLP, simply referred to as the mean elevation of the ski resort (François et al., 2014; Falk and Vanat, 2016). This elevation is strongly correlated ($R^2 = 0.93$) to the median elevation of a ski resort (mean of the minimum and maximum elevations of a ski resort) used by

3. “BD Stations” stands for “Base de Données stations” i.e. a database on French ski resorts

Abegg et al. (2007); Scott et al. (2003) and others. The average difference is - 8 m (standard deviation 91 m).

- The village's elevation of a ski resort is defined as the average of elevations of all urban areas of the resort weighted by their surface area (Breiling and Charamza, 1999).

Please note that ski resorts operated by a single company are aggregated in the present study (François et al., 2014) e.g. Chamonix (le Tour, les Brévents, les Bossons, Montenvers, Aiguille du Midi and Les Grands Montets, all operated by "Compagnie du Mont-Blanc") or the Mercantour ski resorts (Auron, Isola 2000, La Colmiane, all operated by "Cimes du Mercantour").

Spatial representation of ski resorts There is no database that currently includes ski slopes representations (Digital Elevation Models) for all French Alps ski resorts. The geographical location of ski lifts can be used to infer an estimate of resorts ski slopes (François et al., 2014). We refer here to the representation of ski slopes named "gravitational envelopes" (Francois et al., 2016), derived from the ski lifts top and bottom positions and elevations. The resulting envelope of a ski resort corresponds to the ensemble of points that can be reached from the top of a ski lift and from where the bottom of a ski lift can be reached. This is the most consistent approach of skiing practices (i.e. skiers only go downhill). All pixels above 45° steepness are excluded. Due to the limits of the SAFRAN massifs (Figure 6.1), eleven ski resorts were not covered by this meteorological system which reduces the sample of ski resorts which was treated in the present study to 129 ski resorts, representing 804 072 km pers h⁻¹ out of the total 841 958 km pers h⁻¹ in the French Alps i.e. 96% of the total ski lifts infrastructures.

Spatial distribution of snowguns within ski resorts The distribution of snowguns within ski resorts was computed by a method similar to the setup of gravitational envelopes and on literature about snowmaking practices in French ski resorts (Agrawala et al., 2007; Spandre et al., 2015, 2016a). Spandre et al. (2016a) estimated from interviews with professionals that snowmaking was firstly set up on the easiest slopes (accessible to most skiers) to guarantee a minimum skiable area within the ski resort from the top of a selection of ski lifts back down to the resort's village (accomodations). Additionally, Agrawala et al. (2007) reported that 15% of ski slopes were equipped with snowmaking facilities in the French Alps in 2003-2004 and Spandre et al. (2015) estimated that this ratio rose to 32% in 2015 and may reach 43% in 2020. We therefore designed snowmaking envelopes as the areas of ski resorts where slopes are equipped with snowmaking facilities, accounting for three different ratios of equipment (15%, 30% and 45%) and to the following process (Figure 6.2) :

- **Step 1** : the closest ski lifts from the village were selected from an algorithmic approach over three criteria.
 - Distance to the main leisure real estate. Marcelpoil et al. (2012) defined the buildings belonging to a given ski resort as located under a maximum 300 m distance to the bottom of a ski lift. From this selection, Fablet (2013) derived urban areas as buffers around buildings with the corresponding number of buildings included in each area i.e. differentiating isolated versus clustered buildings (Figure 6.2). Our selection areas were defined as 300 m buffers around the clustered urban areas, excluding the isolated buildings.
 - Elevation of buildings. All urban areas with an elevation exceeding the elevation of the ski resort's village by 30% or more were excluded, assuming these are technical buildings or high elevation restaurants without major priority.
 - Significance of urban areas. Five or more buildings within a given urban area were required to consider it as significant, otherwise we did not account for its selection area and did not select

the associated ski lifts (Figure 6.2).

- **Step 2** : the gravitational envelopes of the selected ski lifts were merged and pixels exceeding a 25° slope angle were excluded (assuming the less steep slopes are the easiest ones) to design an initial snowmaking envelope.
- **Step 3** : The ratio of the surface area of this initial snowmaking envelope to the surface of the ski resort's gravitational envelope was compared to the target ratio of equipment (15, 30 or 45%).
 - If lower (Les Deux Alpes example, Figure 6.2), we considered the pixels on the edge of the initial envelope and selected all closest neighbours with higher elevations regardless of the slope angle and repeated the treatment until the target ratio was exceeded. Once higher we moved to the next step.
 - If higher (Les Sept Laux example, Figure 6.2), all pixels starting from the highest elevations of the initial envelope were removed until the target ratio was reached.

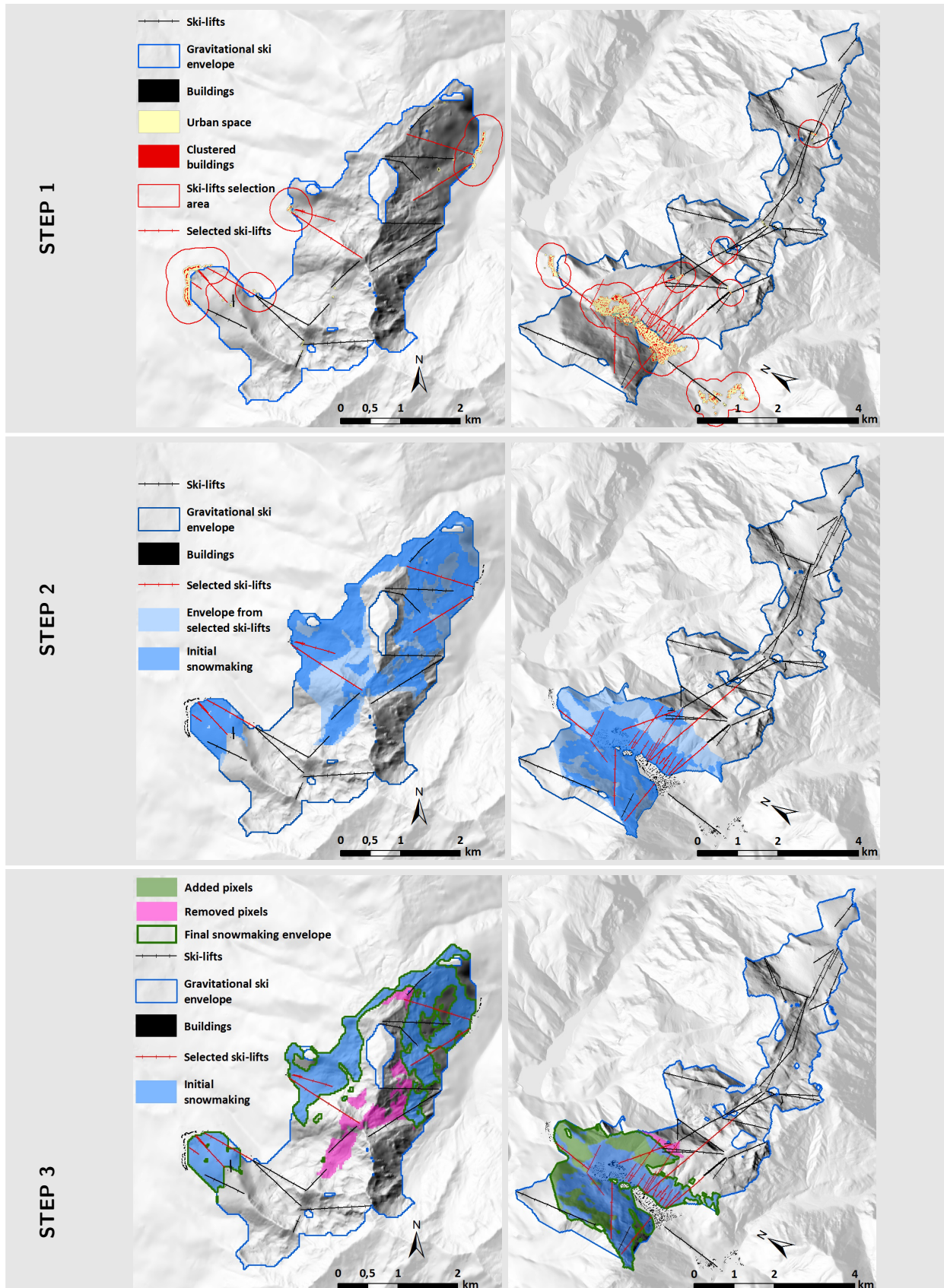


FIGURE 6.2 – Detailed method for the representation of ski slopes covered by snowmaking facilities based on examples in Les Sept Laux (Belledonne, France, left hand side) and Les Deux Alpes (Oisans, France, right hand side) ski resorts. Ski lifts are selected within 300 m from the clustered buildings including five buildings minimum and a limited elevation (Step 1) with their corresponding gravitational envelope, excluding pixels exceeding a 25° angle (Step 2). Pixels are either added or removed to this initial snowmaking envelope to match the target ratio of equipped ski slopes (here 30%) to provide the final snowmaking envelope (Step 3).

The spatial distribution of snowguns within each ski resort was therefore adapted to the characteristics of every ski resort (location of the village, ski lifts). Spandre et al. (2016a) estimated from a survey of a panel of French ski resorts that the maximum elevation of snowguns was significantly correlated to the average elevation of ski lifts ($R^2 = 0.65$, slope = 1.1, $N = 30$). We used the slope of this linear relationship to evaluate the spatial distribution of snowguns simulated by our method (Figure 6.3). The maximum elevation of the simulated snowmaking envelopes was extracted for every ski resort for the three ratios (15%, 30% and 45%) of equipped surface with snowmaking facilities and compared to the average elevation of ski resorts. According to the Pearson product moment correlation test (Onwuegbuzie et al., 2007), the maximum elevation of snowmaking envelopes was significantly correlated to the average elevation of ski lifts for all three ratios with Pearson's correlation coefficients of respectively 0.90, 0.92 and 0.95 for 15%, 30% and 45% ratios ($p\text{-value} = 2.2 \cdot 10^{-16}$ in all cases). The following slopes and correlation coefficients to linear models (R^2) were computed (Figure 6.3) :

- for a 15% ratio, the slope was 1.0 ($R^2 = 0.81$)
- for a 30% ratio, the slope was 1.17 ($R^2 = 0.85$)
- for a 45% ratio, the slope was 1.38 ($R^2 = 0.9$)

The maximum elevations of snowmaking envelopes are correlated with the average elevations of ski lifts facilities which is consistent with findings by Spandre et al. (2016a). The best agreement in terms of slope of the linear model was found for a 30% ratio of equipped ski slope (slope 1.17 vs. 1.1 in Spandre et al. (2016a)), which is furthermore the actual current average ratio reported by Spandre et al. (2015).

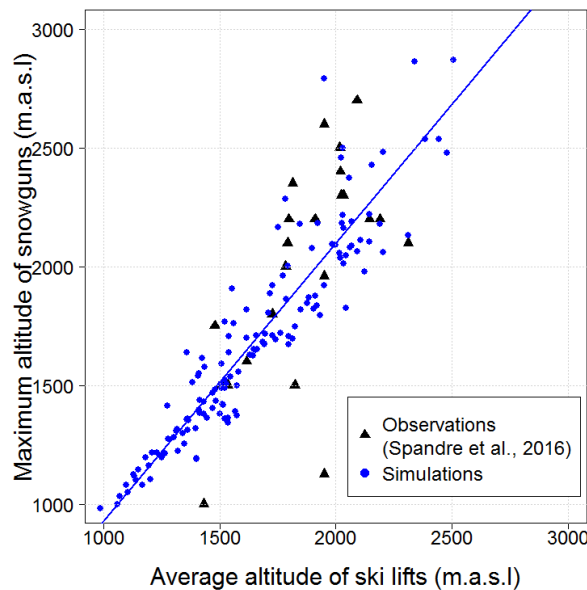


FIGURE 6.3 – Maximum elevation of snowmaking envelopes as designed for the 30% ratio of surfaces equipped with snowmaking facilities with respect to the average elevation of ski lifts facilities for all alpine resorts along with the linear model (slope of 1.17) and the observed data from the survey by Spandre et al. (2016a).

6.3.4 Crossing snow conditions simulations and spatial information of ski resorts

Our approach was based on a previous work by François et al. (2014). Firstly, simulations of snow conditions (snow depth, snow water equivalent) were realized for the 1958 - 2014 period over the 23 different French Alps massifs (Figure 6.1) for all geographical locations in SAFRAN-Crocus : 5 slope angles (0 to 40 °) with 8 distinct aspects (every 45° from North) for all available elevations in a given massif. Secondly, to every pixel within the envelope of a ski resort and characterized by a slope, aspect and elevation information, we assigned simulated snow conditions from SAFRAN-Crocus locations. For example :

- all pixels with a slope angle between 5 and 15° were assigned the snow conditions from the 10° simulation.
- all pixels with an aspect angle between 22.5 and 67.5° were assigned the snow conditions from the 45° simulation.
- all pixels with an elevation between 1350 and 1650 m.a.s.l were assigned the snow conditions from the 1500 m.a.s.l simulation.

When simulating the snow conditions accounting for the production of MM snow, there was an intermediate step defining whether a given pixel was included within the snowmaking envelope or not, then we assigned the corresponding simulation. Last, the ski lift power (SLP) of every single pixel of the envelope of a given ski resort was computed based on the ski lifts elevations and the total SLP of the resort. The aggregated SLP of every altitudinal band (300 m step) was computed from the top and bottom elevations of the ski lifts and shared between the pixels located in the same altitudinal band. For example for a ski lift located between 1200 and 1650 m.a.s.l, we assigned 33% of its SLP to the altitudinal band (1050 - 1350) and 67% to the altitudinal band (1350 - 1650). The aggregated SLP of an altitudinal band was equally shared between pixels located in this band, providing a SLP for every single pixel of the envelope of the ski resort. This weight was used to calculate the viability index of ski resorts, considering a constant weight over the period 1958 - 2014 i.e. computing the integrated snow conditions of ski resorts assuming fixed ski lifts infrastructures.

6.3.5 Economic indicators

We considered in the present study the annual ski lifts tickets sales aggregated at the national level and referred to as “skier days” in the latter, provided by Domaines Skiabiles de France for the 2001 - 2014 period. Although the “BD Stations” contains data on skier days at the scale of a single resort, François et al. (2014) revealed that this information was not available for all resorts in the French Alps, reducing the panel to 105 out of 130 ski resorts. Since the French Alps correspond to a steady 89% of French skier days on average (ODIT, 2009; DSF, 2014), we used the national skier days as a proxy to the French Alps skier days values. The normalized skier days are defined as the annual skier days divided by the mean skier days over the 2001 - 2014 period (thus expressed in %). Please note that the normalized skier days are higher than 100% for winter seasons when skier days are higher than the decadal mean.

6.3.6 Snow reliability indicators for ski resorts

Snow Reliability Line Following Elsasser et al. (2002), Abegg et al. (2007), Steiger (2010) and Pons et al. (2015), we calculated the Snow Reliability Line (SRL) elevation for the 23 alpine massifs over the

1958 - 2014 period based on a threshold of 100 kg m^{-2} of snow for 100 days or more between the 15 December and the 15 April, assuming the snow mass was a more relevant indicator of skiable conditions (Marke et al., 2014; Hanzer et al., 2014). These indicators are referred to as the “Average” and “70% probability” elevations and defined as the elevations where these thresholds are exceeded either on average and for at least seven out of ten winters over the period. The SRL elevation was computed based on the simulations of groomed snow conditions (no production) for SAFRAN locations with 0° slope angle (thus irrespective of ski resorts characteristics). We used a linear interpolation between durations computed for SAFRAN/Crocus elevations (300 m steps) to provide the exact elevation corresponding to a 100 days season duration. Beyond this initial step, we computed the SRL elevation accounting for snowmaking (formulation in section 6.3.2), referred to as “With Snowmaking”. We also applied a stricter threshold to calculate the SRL elevation “With Snowmaking” following Steiger and Mayer (2008), and considered the elevation for which nine out of ten winter seasons are snow reliable i.e. have a snowpack of 100 kg m^{-2} for 100 days or more. We further compared these three SRL elevations to the elevations of the village and of ski lifts for all 129 ski resort of French Alps massifs.

Viability index Snow reliability indicators were computed for ski resorts for every single day between the 1 November and the 15 May either based on snow depth (a pixel was declared snow-reliable if the simulated snow depth exceeded 30 cm) or on snow mass (a pixel was declared snow-reliable if the simulated snow mass exceeded 100 kg m^{-2} i.e. 20 cm of snow with a density of 500 kg m^{-3}). Since we considered that the snow mass was a more relevant indicator of suitable conditions for skiing (Steiger, 2010; Marke et al., 2014; Spandre et al., 2016c), all results in this study are based on the snow mass definition, unless explicitly specified. The SLP of snow-reliable pixels were summed to provide an integrated snow-reliable SLP ranging between 0 and the total SLP of the ski resort. The daily viability index was defined as the ratio of the daily snow-reliable SLP of a given resort to the total SLP of this resort, therefore ranging between 0 and 1 (usually expressed in %). Three distinct viability index were calculated based on the records of the French Ministry of Education (Ministère de l'Education Nationale de l'Enseignement Supérieur et de la Recherche, 2016). For each of these three periods (see below) we computed the mean of daily viability index for every ski resort and every winter season.

- Christmas and New year holidays (20 December - 5 January)
- Winter school holidays (5 February - 5 March)
- Season (15 December - 15 April)

These viability indexes can be further aggregated for all 129 French Alps ski resorts together, for categories of ski resorts (Table 6.1) or geographical locations (French departments, Northern/Southern Alps) weighted by individual SLP of resorts. In the present study we defined two snow reliability indicators.

- The “Season” viability index (average index between the 15 December and the 15 April)
- The “Combined holidays” viability index (CHVI) of the Christmas and New-Year holidays viability index (CNY) and the Winter school holidays viability index (WS). This was computed for every winter season considering a relative weight c from $c = 0$ (WS viability index only) to $c = 1$ (CNY viability index only)

$$\text{CHVI} = c * \text{CNY} + (1 - c) * \text{WS} \quad (6.1)$$

These two snow reliability indicators were computed for the snow conditions accounting for natural snow only, the groomed snow and the groomed snow plus snowmaking with a 15, 30 and 45% ratios of equipped ski slopes with snowmaking facilities. The correlation of skier days with both the “Season” and the “Combined holidays” viability index was computed and discussed for these five configurations.

6.3.7 Computation of water and energy requirements

The physically based approach of snowmaking in Crocus-Resort combined with the spatial information of ski resorts allows deriving for every pixel of a given ski resort the daily amount of MM snow produced, expressed in kg m^{-2} . From this information the total amount of water used for production can be computed for every resort on every season and aggregated to provide the total water consumption over the French Alps for a given winter season for a 15, 30 or 45% ratio of equipped ski slopes with snowmaking facilities. Please note this computation does not account for water losses during the snowmaking process. This analysis required two informations to carry estimations of actual water consumptions : the time evolution of the ratio of ski slopes equipped with snowmaking facilities (Spandre et al., 2015) and an estimated ratio between the gravitational envelopes surface area and the actual ski slopes surface area (François et al., 2014), see below.

Evolution of facilities The time evolution of the ratio of equipped ski slopes with snowmaking facilities was taken from the literature (Hahn, 2004; Abegg et al., 2007; ODIT, 2009; Spandre et al., 2015) for every winter season over the 1985 - 2014 period i.e. from the beginning of snowmaking facilities in the French Alps. For a given winter season, the water consumption was calculated based on the simulated water volumes for 15, 30 and 45% ratios and on the exact ratio of equipped ski slopes for this specific winter season. This was done to reduce the required computations using the spatial representations of equipped ski slopes for only three ratios (15, 30 and 45%) instead of one spatial representation every year (30 spatial representations). If the ratio was below 15% of equipped ski slopes (i.e. before 2004), the water volume was computed proportionally to the simulated water consumption for a 15% ratio. If the ratio was between 15% and 30% of equipped ski slopes (i.e. between 2004 and 2013), the water volume was computed proportionally to the simulated water consumptions for the 15% and 30% ratios. The same was applied between 30% and 45% ratios (after 2013). This provided aggregated water volumes accounting for the gravitational envelopes. We estimated the actual consumption thanks to the assessment of the ratio between gravitational envelopes and actual ski slopes surface area.

From gravitational envelopes to actual ski slopes The gravitational envelopes actually describe the potential slopes than could be used for skiing although ski tracks may be limited to a smaller part of this area. François et al. (2016) estimated from a panel of 44 French Alps ski resorts (Spandre et al., 2015, 2016a) that the actual ski slopes cover on average 11% (standard deviation 4%) of the gravitational envelopes surface area. The total surface area of the gravitational envelopes of the 129 French Alps ski resorts is 146 666 hectares providing an estimate of the actual ski slopes surface area of 16 133 ha (± 5867 ha). The total surface areas equipped with snowmaking facilities for 15, 30 and 45% ratios were calculated using the same ratio (11% \pm 4%) from the snowmaking envelopes (Section 6.3.3) and were estimated to 2406 ha (± 875 ha) for a 15% ratio, to 4812 ha (± 1750 ha) for a 30% ratio and to 7194 ha (± 2616 ha) for a 45% ratio.

Energy consumption The energy consumption for snowmaking was computed from the simulated water volumes and using an energy consumption per m^3 of water from the literature (Rixen et al., 2011; Hahn, 2004). Rixen et al. (2011) reported values of the energy consumption for the production of MM snow from records in Davos and Scuol (Switzerland) and estimated an average 5 to 6.3 kWh per m^3 of water used for snowmaking i.e. respectively 1.0 to 1.25 and 1.7 millions of kWh (GWh) for the production of 0.2 and 0.3 millions of m^3 of water (Mm^3). Similarly Hahn (2004) estimated a total

consumption of energy dedicated to the production of MM snow in the Alps of 600 GWh required for the production of 95 Mm³ of water into snow i.e. an average 6.3 kWh m⁻³. We retained an average energy consumption of 6 kWh per m³ of water with an uncertainty of 1 kWh m⁻³ (an additional 17% to the uncertainty on the water volume) for further calculations.

6.4 Results

6.4.1 Computation of season duration using snow depth and mass

In the present study, the season duration with suitable conditions for skiing was computed for the 1958 - 2014 period at all SAFRAN-Crocus elevations (flat slope), between the 15 December and 15 April as the number of days when snowpack exceeded either 30 cm (SD) or 100 kg m⁻² (SWE, Figure 6.4). In natural snow, the season duration was 3 to 4 days shorter on average when based on SWE compared to the calculation based on snow depth. The maximum difference was found at an elevation of 1500 m.a.s.l (5 days in the Northern Alps) to 1800 m.a.s.l (7 days in the Southern Alps). When accounting for grooming (no production) the season duration was 8 to 10 days longer on average when based on SWE compared to the calculation based on snow depth. The maximum difference was found at an elevation of 900 m.a.s.l in the Northern Alps (18 days) and at an elevation of 1500 m.a.s.l in the Southern Alps (18 days).

The computation based on snow depth suggested that the season duration in groomed snow conditions was on average 9 days shorter than in natural snow conditions in the Northern Alps and 13 days shorter in the Southern Alps (Figure 6.4) with a maximum difference at 900 and 1200 m.a.s.l in the Northern Alps (15 days) and 1500 m.a.s.l in the Southern Alps (22 days). On the contrary, calculations based on SWE showed that the season duration in groomed snow conditions was 2 days longer compared to the natural snow on average in the Northern Alps (maximum 6 days at an elevation of 900 m.a.s.l) and one day in the Southern Alps (maximum 3 days at an elevation of 1500 m.a.s.l). In order to provide consistent values of the season duration that could be compared, all further computations of the season length were based on the snow mass (SWE), following Steiger and Mayer (2008) and Marke et al. (2014) who suggested that the snow mass on the ground (kg m⁻²) was the most relevant criteria to evaluate the skiing conditions.

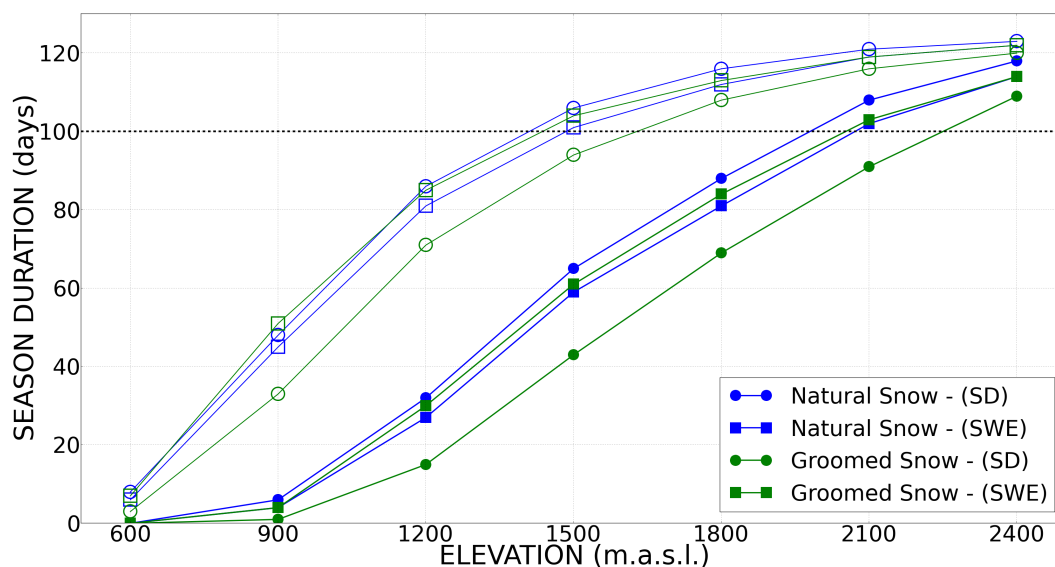


FIGURE 6.4 – The average season duration of natural snow and groomed snowpacks between the 15 December and 15 April when exceeding 30 cm (SD) or 100 kg m⁻² (SWE) over the 1958 - 2014 period, for SAFRAN-Crocus elevations from 600 to 2400 m.a.s.l. Empty markers correspond to the Northern Alps (average) and filled markers to the Southern Alps (average).

6.4.2 Analysis of village and ski lifts elevation versus the Snow Reliability Line elevation

Natural snow conditions The Snow Reliability Line (SRL) “Average” elevation over the 1958 - 2014 period (Figure 6.4) was 1480 m.a.s.l in the Northern Alps (standard deviation 187 m) and 2035 m.a.s.l in the Southern Alps (standard deviation 180 m). It was interesting to note that the computed SRL “Average” elevation was slightly lower over the 2005 - 2014 decade (1400 and 1960 m.a.s.l for the Northern and Southern Alps) than over the 1958 - 2014 period (Table 6.2). The SRL “70% probability” elevation (Table 6.3) was strongly correlated to the SRL “Average” elevation (correlation coefficient $R^2 = 0.985$) with an average offset of + 94 m (standard deviation 43 m) for the “70% probability” elevation over all massifs. The variability over time (Table 6.2) and space (Table 6.3) was significant, accordingly to previous investigations (Durand et al., 2009a).

	Snow Reliability Line “Average” elevation (m.a.s.l)					1958 - 2014
	1965 - 1974	1975 - 1984	1985 - 1994	1995 - 2004	2005 - 2014	
Northern Alps	1030	900	1550	1510	1400	1480
Southern Alps	1940	1890	2240	2040	1960	2035

TABLE 6.2 – Snow Reliability Line elevation computed for the Northern and Southern French Alps for the 1958 - 2014 period based on groomed natural snow conditions (no production). SRL elevations are detailed for all massifs in Table 6.3.

The number (n) of ski resorts located above the SRL elevations were reported in Table 6.3 for both the village and ski lifts elevations, along with the total number (N) of resorts in the massif. 6 Small resorts villages out of 55 (11%) are located above the SRL “Average” elevation while the average ski lifts elevation exceeds the SRL “Average” elevation for 20 of them (36%). On the contrary 8 out

of the 14 Very Large resorts are located above the SRL “Average” elevation (57%) and 13 have an average ski lifts elevation above it (93%). This confirms the relationship between the elevation of a ski resort and its size (François et al., 2014). Overall, 25 out of 129 resorts’ villages are located above the SRL “Average” elevation (19%), none of them being located in the Southern Alps. Respectively 41% and 38% of resorts located in the departments of Hautes-Alpes and Isère have an average ski lifts elevation above the SRL “Average” elevation and respectively 84 and 82% of those located in Savoie and Haute-Savoie . Outside these departments (Alpes Maritimes, Alpes de Haute Provence, Drôme) no resorts have ski lifts located above the SRL “Average” elevation. Overall, 80 out of 129 resorts have an average ski lifts elevation above the SRL “Average” elevation (62%) and 71 (55%) above the “70% probability” elevation.

Impact of snowmaking The SRL elevation “With Snowmaking” was computed over the 1958 - 2014 period and reported in Table 6.3 for the 23 alpine massifs. 12 massifs out of the 23 were snow reliable at the lowest SAFRAN elevation when accounting for snowmaking. In these massifs and at the minimum SAFRAN elevation, the probability of exceeding 100 kg m^{-2} for 100 days or more was higher than 90%, which we reported in the Table 6.3. The snow reliability when accounting for snowmaking was guaranteed at the ski lifts elevation for all French Alps ski resorts except for two (one in Oisans and one in Devoluy). This resulted in a 98% snow reliability of French Alps ski lifts accounting for snowmaking and according to the Snow Reliability Line approach. Regarding the elevation of villages, eleven of them had elevations lower than the computed SRL elevation “With Snowmaking” (one in Chablais, one in Aravis, one in Mont-Blanc, five in Vercors, two in Oisans and one in Devoluy). Snowmaking can therefore guarantee the snow reliability at the village elevation for 118 out of 129 ski resorts (91%) according to the Snow Reliability Line approach (Abegg et al., 2007; Steiger and Mayer, 2008).

Massif	Snow Reliability Line Elevation (m.a.s.l)			Total (N)	Number (n) of ski resorts above the SRL					
					at Village elevation			at Ski Lifts elevation		
	GS Av.	GS > 70%	GS+SM > 90%		GS Av.	GS > 70%	GS+SM > 90%	GS Av.	GS > 70%	GS+SM > 90%
Chablais	1309	1372	870 (90%)	18	3	3	17	15	14	18
Aravis	1257	1323	750 (96%)	13	1	0	12	8	6	13
Mont-Blanc	1343	1415	1050 (100%)	7	1	0	6	7	6	7
Bauges	1301	1348	814 (90%)	4	1	1	4	4	4	4
Beaufortain	1368	1463	750 (91%)	5	1	0	5	5	4	5
Haute-Tarentaise	1479	1617	750 (93%)	5	4	4	5	5	5	5
Chartreuse	1401	1476	867 (90%)	6	0	0	6	1	0	6
Belledonne	1410	1463	850 (90%)	3	2	1	3	3	3	3
Maurienne	1478	1613	729 (90%)	7	6	2	7	7	7	7
Vanoise	1574	1715	750 (96%)	11	4	3	11	10	11	11
Haute-Maurienne	1942	1988	1050 (98%)	6	0	0	6	3	3	6
Grandes Rousses	1639	1773	750 (91%)	3	2	0	3	3	3	3
Tabor	1895	1958	1350 (95%)	2	0	0	2	1	1	2
Vercors	1537	1611	1125 (90%)	10	0	0	5	1	0	10
Oisans	1705	1841	1100 (90%)	8	0	0	6	3	2	7
Pelvoux	1767	1898	1050 (100%)	3	0	0	3	2	2	3
Queyras	2209	2334	1050 (100%)	1	0	0	1	0	0	1
Devoluy	1859	1904	1385 (90%)	2	0	0	1	0	0	1
Champsaur	1880	1978	1050 (98%)	3	0	0	3	1	1	3
Embrunais-Parpaillon	2183	2334	1020 (90%)	3	0	0	3	1	0	3
Ubaye	2219	2398	1050 (90%)	4	0	0	4	0	0	4
Haut-Var - Haut-Verdon	2137	2165	1433 (90%)	4	0	0	4	0	0	4
Mercantour	2167	2229	1460 (90%)	1	0	0	1	0	0	1
Northern Alps	1480	1570	870	106	25	14	96	75	67	105
Southern Alps	2035	2130	1170	23	0	0	22	5	4	22

TABLE 6.3 – Snow Reliability Line (SRL) elevation (m.a.s.l) for the 23 alpine massifs for the 1958 - 2014 period based on a threshold of 100 kg m⁻² of snow for 100 days or more between the 15 December and the 15 April. Southern Alps massifs are highlighted in dark grey, Northern Alps massifs in grey. “GS Av.” and “GS >70%” SRL refer to elevations where these thresholds are exceeded either on average or for at least 7 out of 10 winters of the period accounting for the groomed snow conditions. “GS+SM >90%” SRL refers to the elevation where these thresholds are exceeded for at least 9 out of 10 winters of the period accounting for grooming and snowmaking. In this case we indicated the elevation of the SRL and detailed the probability of threshold exceedance since the lowest SAFRAN elevation was snow reliable when accounting for snowmaking for 12 massifs out of 23 i.e. had a probability higher than 90%. The total number (N) of ski resorts in a given massif is indicated along with the number (n) of ski resorts located above the different SRL elevations with respect to the “Village” or the “Ski lifts” elevations.

6.4.3 Correlation between skiers days and viability index

All relationships between the skier days and either the “Season” or the “Combined holidays” viability index were statistically significant according to the Pearson product moment correlation test (Onwuegbuzie et al., 2007) with correlation coefficients higher than 0.86 and p-values below 10⁻⁴ (Table 6.4). The correlation coefficient of skier days with the “Season” viability index based on natural snow conditions was R² = 0.86, similarly to the correlation computed by François et al. (2014). According to this

approach, a 1% increase in the season viability index corresponds to a 0.46% increase in the normalized skier days. If accounting for grooming and a 30% ratio of equipped ski slopes with snowmaking facilities, a 1% increase in the season viability index corresponds to a 0.69% increase in normalized skier days ($R^2 = 0.77$). According to this formulation of the season viability index, the variability of snow conditions in ski resorts remains higher than the variability of skier days, regardless the equipment in snowmaking facilities (a 1% change of snow conditions corresponds to a <1% change in normalized skier days). Regarding the correlation of skier days with the “Combined holidays” viability index, the highest correlation ($R^2 = 0.91$) accounting for natural snow conditions was found for a relative weight $c = 22\%$ of Christmas and New-Year holidays versus the winter school holidays (Figure 6.5, grey curve). A 1% increase in the “Combined holidays” viability index based on natural snow cover corresponds to a 0.57% increase in normalized skier days.

	Natural Snow	Grooming only	With 15% Snowmaking	With 30% Snowmaking	With 45% Snowmaking
“Season” viability index					
Correlation coefficient (R^2)	0.86	0.83	0.80	0.77	0.74
Increase in normalized skier days for a 1% increase of the viability index (%)	0.45	0.49	0.59	0.69	0.82
“Combined holidays” viability index					
Optimal weight c	0.22	0.17	0.165	0.17	0.18
Optimal correlation coefficient (R^2)	0.91	0.89	0.86	0.87	0.86
Increase in normalized skier days for a 1% increase of the viability index (%)	0.57	0.68	0.85	1.02	1.26

TABLE 6.4 – Correlation of skier days with the “Season” and “Combined holidays” viability index with relative impacts on normalized skier days accounting for the different snow conditions (natural, groomed, with snowmaking) over the 2001 - 2014 period.

The impact of a 1% increase of the viability index on the normalized skier days shows a significantly higher sensitivity to the ratio of equipped ski slopes when based on the “Combined holidays” index (Table 6.4), particularly compared to the “season” viability index. According to this formulation of the “Combined holidays” viability index, a 1% change in the snow conditions corresponds to a 1% change in normalized skier days for a ratio of equipped ski slopes with snowmaking facilities between 15 and 30%. The relative evolution of the “Combined holidays” viability index to its average over the 2001 - 2014 period is very consistent with the normalized skier days when accounting for snowmaking (Figure 6.5).

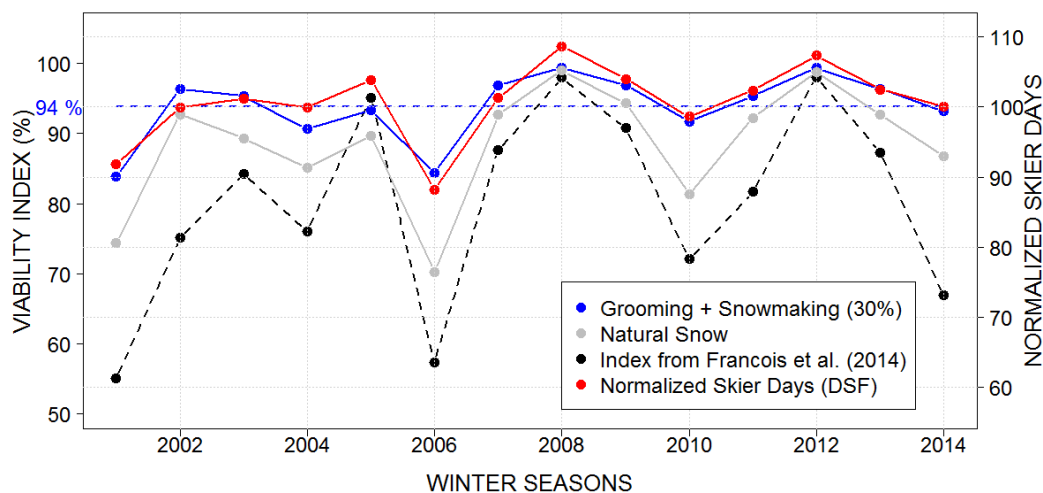


FIGURE 6.5 – The “Combined holidays” viability index (%) based on natural snow and on managed snow simulations (30% of equipped surface with snowmaking facilities), for the 2001 - 2014 period, along with the normalized skier days (as the ratio of annual versus 2001-2011 average) aggregated at the national level (DSF) and the viability index from François et al. (2014). Both y-axis have identical scales with the 100% normalized skier days centered on the average “Combined holidays” viability index over the 2001 - 2014 period (94%).

6.4.4 Time variations of the viability index

All results in this section were based on the “Combined holidays” viability index aggregated for all French Alps ski resorts and used a value of the weighing coefficient $c = 0.17$, consistently with most results of Table 6.4. The viability index showed a significant variability over the past five decades (Table 6.5), ranging between 84.4% (1985 - 1994) and 93.8% (1975 - 1984) under natural snow conditions with an average 88.8%. The variability (standard deviation) of the viability index decreased with grooming and snowmaking. Hypothetically, the variability of the viability index over the 1958 - 2014 period would have been 7.9% if ski slopes had been covered by snowmaking facilities as they were in 2015 (30%, Spandre et al. (2015)) versus 12.1% under natural snow conditions (Table 6.5). The variability (standard deviation) of the viability index for the Christmas and New-Year holidays was 22.9% based on natural snow conditions (1958 - 2014 period) versus 11.7% for the Winter school holidays. The aggregated viability index of the Christmas and New-Year holidays and of winter school holidays did not show any significant evolution since 1958 due to this large interannual variability, regardless the inclusion or not of grooming and snowmaking. There was no statistically significant evolution of the viability index accounting for grooming and snowmaking either for the Christmas holidays and the winter school holidays (data not shown).

Management mode	Average viability index (%)					Period 1958 - 2014
	Decadal					
	1965 - 1974	1975 - 1984	1985 - 1994	1995 - 2004	2005 - 2014	
Natural snow	92.0 (± 5.1)	93.8 (± 4.2)	84.4 (± 11.3)	88.5 (± 6.3)	89.8 (± 8.6)	88.8 (± 12.1)
Groomed snow	92.6 (± 4.9)	94.2 (± 4.0)	85.2 (± 11.1)	89.9 (± 6.5)	91.5 (± 7.1)	89.7 (± 11.9)
Managed snow (15%)	94.3 (± 3.7)	95.5 (± 3.1)	88.3 (± 8.9)	92.2 (± 5.3)	93.5 (± 5.5)	91.9 (± 9.7)
Managed snow (30%)	95.4 (± 2.9)	96.3 (± 2.5)	90.4 (± 7.3)	93.6 (± 4.3)	94.7 (± 4.4)	93.4 (± 7.9)
Managed snow (45%)	96.2 (± 2.3)	97.0 (± 1.9)	92.3 (± 5.8)	94.8 (± 3.4)	95.7 (± 3.5)	94.7 (± 6.2)

TABLE 6.5 – Evolution of the aggregated viability index for all French Alps ski resort over the 1965 - 2014 five decades under natural snow, groomed natural snow and groomed natural snow plus snowmaking conditions with the three ratios of equipped ski slopes with snowmaking facilities (15, 30 and 45%). For each period the **average index** (± the standard deviation) is provided.

It was interesting to note that during the 1985 - 2014 period, five winter seasons showed a “Combined holidays” viability index (in natural snow conditions) lower than 80% (1988, 1989, 1992, 2001 and 2006), with an average value of 70.8% (±3.2%). Accounting for an hypothetical ratio of equipment in snowmaking facilities of 45%, the average aggregated viability index for these five winters would have been 85.6% (±2.6%), equivalent to the 1985 - 1994 average viability index under groomed natural snow. Overall, the relative impact on the simulated viability index decreased with increasing ratios of equipped ski slopes with snowmaking facilities (Figure 6.6, Table 6.5).

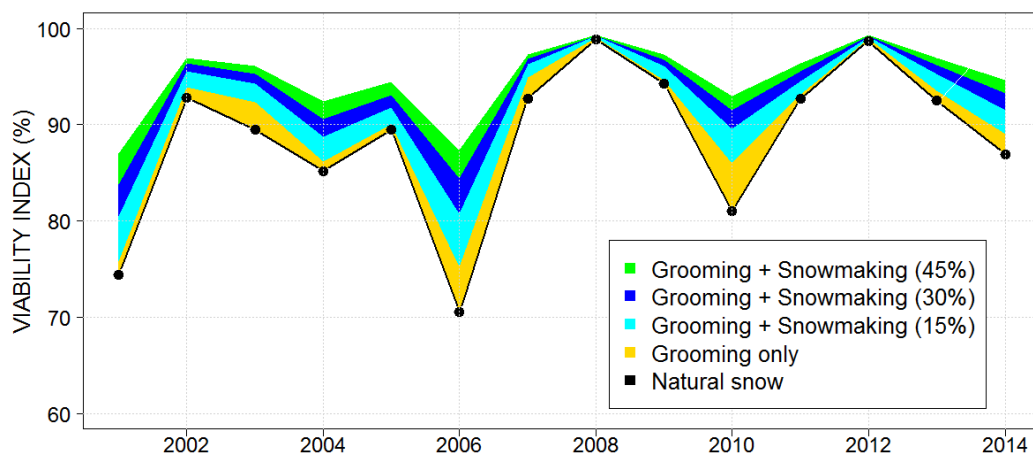


FIGURE 6.6 – Evolution of the viability index (%) over the 2001 - 2014 period from the present study, based on natural and managed snow simulations with the relative impacts of grooming only, and combined with 15%, 30% and 45% ratios of equipped ski slopes with snowmaking facilities. The baseline (black curve) is the viability index computed for the natural snow conditions.

6.4.5 Impact of resorts location and size

Consistently with the spatial variability revealed in Section 6.4.2, the “Combined holidays” viability index showed a significant geographical pattern within the French Alps (Table 6.6, Figure 6.7). The Southern Alps ski resorts had both lower average and higher variability (standard deviation) values of the viability index over the 1958 - 2014 period. The correlation of the regional viability index based on

natural snow conditions with the national skier days was also poorer in the Southern Alps ($R^2 = 0.49$, $p\text{-value} = 0.005$) compared to the Northern Alps ($R^2 = 0.84$, $p\text{-value} = 4 \cdot 10^{-6}$), suggesting that the Northern Alps may be the major driver of annual skier days and that the ski market in the Southern Alps might differ from the Northern Alps with contrasted impacts of poor snow seasons on the economic success of the season.

Viability Index (%) Period 1958 - 2014	Alpes de Haute Provence (04)	Hautes Alpes (05)	Alpes Maritimes (06)	Drôme/Isère (26 and 38)	Savoie (73)	Haute Savoie (74)
natural snow	63.9 (± 26.6)	83.6 (± 17.0)	69.5 (± 25.7)	89.0 (± 12.8)	92.2 (± 11.1)	90.2 (± 13.8)
Snowmaking (30%)	79.9 (± 17.0)	90.2 (± 11.3)	79.6 (± 18.5)	94.0 (± 8.1)	95.4 (± 7.1)	94.2 (± 9.5)

TABLE 6.6 – **Average viability index** (\pm Standard Deviation) of ski resorts over the 1958 - 2014 period with respect to the administrative department they belong to, under natural snow conditions and including grooming and a 30% ratio of equipped ski slopes with snowmaking facilities. The Northern Alps regroup all resorts located in Savoie, Haute Savoie, Isère and Drôme while the Southern Alps regroup all resorts located in Hautes Alpes, Alpes Maritimes and Alpes de Haute Provence.

Focusing on the size of ski resorts (Table 6.7), the correlation between the “Combined holidays” viability index and skier days of Very Large resorts was significantly lower than for the other categories ($R^2 = 0.79$ in natural snow conditions, versus 0.89, 0.91 and 0.92 for S, M and L categories). The variability of the viability index computed for natural snow conditions in ski resorts was higher than the variability of skier days, regardless the resorts categories (a 1% change of snow conditions corresponds to a $<1\%$ change in normalized skier days). Accounting for grooming and a 30% ratio of equipped ski slopes with snowmaking facilities, the variability of the viability index remained higher than the variability of skier days for S, M and L resorts categories although not for XL resorts category (a 1% change of snow conditions in XL resorts corresponded to a 1.3% change in normalized skier days). The larger the resorts, the better their average snow conditions were, along with the lower variability (Table 6.7).

Viability Index (%) Period 1958 - 2014	Small Resorts (S)	Medium Resorts (M)	Large Resorts (L)	Very Large Resorts (XL)
Natural snow	82.7 (± 16.8)	83.5 (± 15.0)	87.4 (± 13.5)	92.1 (± 9.9)
Snowmaking (30%)	89.7 (± 11.6)	90.4 (± 9.9)	92.7 (± 8.9)	95.2 (± 6.3)

TABLE 6.7 – **Average viability index** (\pm Standard Deviation) of ski resorts over the 1958 - 2014 period with respect to the category they belong to (Table 6.1) under natural snow conditions and including grooming and a 30% ratio of equipped ski slopes with snowmaking facilities.

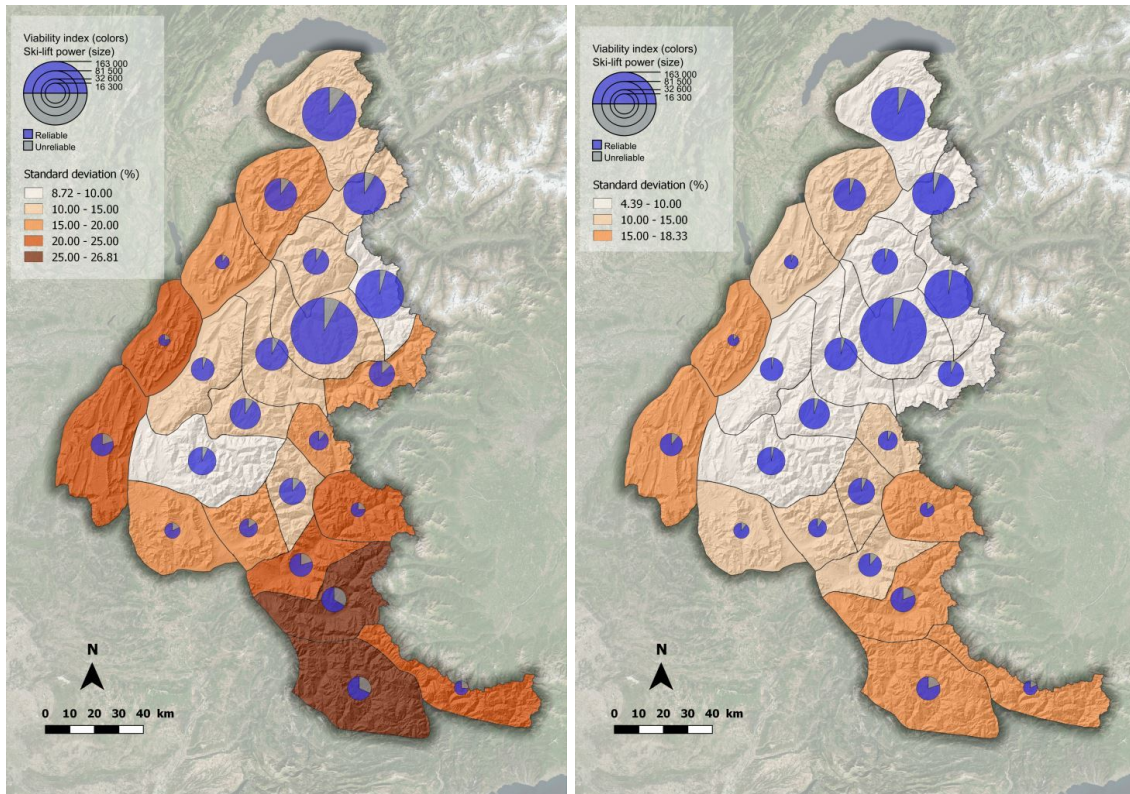


FIGURE 6.7 – Snow reliability of the 23 alpine massifs for the 1958 - 2014 period based on the aggregated “Combined holidays” viability index for each massif and computed for the natural snow conditions (left) and the groomed plus a 30% snowmaking ratio snow conditions (right). For each massif the pie chart corresponds to the average viability index and the filling color corresponds to the variability (standard deviation) of the viability index for the 1958 - 2014 period. The surface area of pie charts is proportional to the total ski lift power for each massif.

6.4.6 Computation of water and energy consumption for snowmaking

Water dedicated to snowmaking The computed water consumption for snowmaking (regardless of water losses, Section 6.3.7) ranged between a minimum $1509 \text{ m}^3 \text{ ha}^{-1}$ to a maximum $3072 \text{ m}^3 \text{ ha}^{-1}$ with an average $1982 \text{ m}^3 \text{ ha}^{-1}$ and a standard deviation of $390 \text{ m}^3 \text{ ha}^{-1}$ over the 1985 - 2014 period. Accounting for a 500 kg m^{-3} MM snow density, this corresponds to a minimum 30.1 cm, a maximum 61.4 cm and an average 39.6 cm MM snow thickness on equipped ski slopes. The production per hectare of ski slope was very similar between simulations accounting for 15, 30 or 45% ratios. The difference was due to the higher elevations of additional pixels between 15 and 30% ratios and thus the decreasing need for MM snow (and similar between 30 and 45% ratios). On average over the 1985 - 2014 period the amount of MM snow produced per surface of ski slope accounting for a ratio of 15% was $1997 \text{ m}^3 \text{ ha}^{-1}$, $1930 \text{ m}^3 \text{ ha}^{-1}$ for a 30% ratio and $1886 \text{ m}^3 \text{ ha}^{-1}$ for a 45% ratio. Rixen et al. (2011) reported similar values from observations of snow production in Davos and Scuol (Switzerland) with $300\,000 \text{ m}^3$ and $200\,000 \text{ m}^3$ of water used for 150 and 144 hectares ski areas i.e. respectively 2000 and $1390 \text{ m}^3 \text{ ha}^{-1}$ of water used for snowmaking. Our computations did not reveal any statistically significant evolution of the amount of MM snow produced per hectare of ski slopes over the 1985 - 2014 period.

The main driver of the increase of the water consumption for snowmaking remained the evolution of the ratio of equipped ski slopes with snowmaking facilities (Figure 6.8).

The total amount of water was estimated to 4.3 millions m^3 (Mm^3 , $\pm 1.5 Mm^3$) on average for the 2002 - 2004 period when the ratio of equipped ski slopes was 15% (Hahn, 2004) and to 10.2 Mm^3 ($\pm 3.7 Mm^3$) on average for the 2012 - 2014 period when the ratio reached 30% (Spandre et al., 2015). If the ratio of equipped ski slopes was to reach 45% as expected by Spandre et al. (2015) in 2020, the water consumption (if encountering the same climate conditions as over the 1985 - 2014 period) would be on average 13.6 Mm^3 ($\pm 4.9 Mm^3$) with a minimum 10.9 Mm^3 and a maximum 21.1 Mm^3 . Due to the uncertainty on the ratio between the actual surface area of ski slopes and the gravitational envelopes surface area, the resulting uncertainty over the total volume of water was estimated to be about 36%. However such uncertainty applied on the absolute value of required water, the relative change was expected not to be affected.

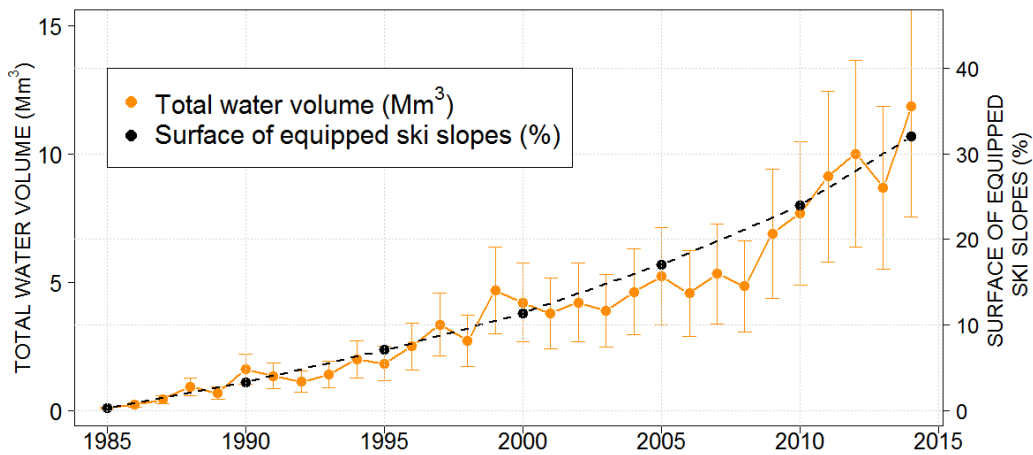


FIGURE 6.8 – Water volumes used for snowmaking per hectare of equipped ski slopes ($m^3 ha^{-1}$). The total water volume consumption (in millions of m^3 , Mm^3) is the product of the water volume per hectare with the total surface of equipped ski slopes, accounting for the uncertainty on the ratio between gravitational envelopes and actual ski slopes surfaces. The evolution of the surface of equipped ski slopes with snowmaking facilities (Spandre et al., 2015) is the main driver of the increase of the total water volume used for snowmaking within the 1985 - 2014 period.

Associated energy consumption The energy consumption for snowmaking was computed from the estimated water volumes (regardless of water losses) and using an energy consumption of 6 kWh per m^3 of water ($\pm 1 kWh m^{-3}$). The total energy consumption was estimated to 25.5 GWh ($\pm 13.5 GWh$) on average for the 2002 - 2004 period when the ratio of equipped ski slopes was 15% (Hahn, 2004) and to 61.0 GWh ($\pm 32.3 GWh$) on average for the 2012 - 2014 period when the ratio reached 30% (Spandre et al., 2015). If the ratio of equipped ski slopes was to reach 45% as expected in 2020 by Spandre et al. (2015), the energy consumption for snowmaking (if encountering the same climate conditions as over the period 1985 - 2014) would be on average 81.4 Mm^3 ($\pm 43.1 GWh$) with a minimum 65.1 GWh and a maximum 126.8 GWh.

6.5 Discussion

6.5.1 Snow Reliability Line and viability index

The definition of the SRL allows computing in a simple approach the vulnerability of a ski resort with minimum requirements. The SRL revealed the strong geographical pattern between all French Alps massifs and differences between resorts categories (Section 6.4.2) which was confirmed by the viability index (Section 6.4.3). The SRL also provides a binary assessment reliable/not reliable which may be easier to use when communicating on potential impacts e.g. of climate change on the ski industry, by counting the number of reliable ski resorts. This can not be done using the viability index which would require to assess a minimum level that could be considered as reliable. However, the SRL approach shows clear limitations when accounting for the impact of snowmaking or to predict economic implications of seasons with poor snow conditions since the SRL fails to provide informations on the consequences of any changes in the snow conditions beyond a binary assessment. Snowmaking was confirmed to be an efficient method to mitigate the effects of the deficit of snow on the viability of ski resorts. However, all slopes are not equipped with snowmaking facilities in France in 2015, which is impossible to take into account by the SRL approach and hampers any detailed investigation of snowmaking requirements (water volumes and related energy costs). Similarly the present study showed in agreement with Scott et al. (2006); Falk and Hagsten (2016) that specific periods of the season had overproportional economic importance (holidays) which can not be used or revealed by the SRL approach. Last, the SRL relies on a single location to represent ski resorts which choice is highly subjective. The SRL approach therefore remains an efficient method to provide information within a minimum time and means, including the capacity to be easily transferred to distinct locations and time periods or used for large scale investigations. However detailed implications of changes in the snow conditions should be undertaken with more robust methods and indicators such as the viability index, or any equivalent approach.

6.5.2 Relationship between snow viability index and skier days

The highest correlation coefficient between skier days and the aggregated "Combined holidays" viability index (Section 6.4.3) was found for natural snow conditions ($R^2 = 0.91$), with lower correlation coefficients when accounting for the impact of grooming and snowmaking ($R^2 = 0.86$ to 0.89). This suggests that the variability of the skier days is based on the natural variability of the snow conditions with the management of the snow counteracting this variability. Therefore the occurrence of a change in the skier days is best predicted by a change in the natural snow conditions. However the magnitude of the impact of this change on the skier days is best predicted when accounting for grooming and a 15 to 30% ratio of equipped ski slopes with snowmaking facilities (period 2001 - 2014). This statistical relationship is consistent with the actual ratio of equipment over the 2001 - 2014 period with 12.6% of equipped ski slopes in 2001 and 32% in 2014 (Spandre et al., 2015). Moreover the relative weight of the Christmas and New-Year holidays versus the winter holidays was derived from a statistical approach which purpose was to figure out which relative weight provided the highest correlation between skier days and the aggregated "Combined holidays" viability index. This relative weight was found between 16.5 and 22% which is consistent with the estimated economic importance of the Christmas and New-Year holidays (Lecuret et al., 2014).

6.5.3 Misinterpretations of using snow depth to assess the viability

Observations of ski slopes snowpacks density always reported significantly higher values than for natural snowpacks (Fahey et al., 1999; Steiger and Mayer, 2008; Spandre et al., 2016c). All investigations of the vulnerability of snow related activities accounting for snow management (grooming, snowmaking) should therefore account for such differences otherwise major misinterpretations may occur. When comparing the groomed versus natural snowpack conditions (Section 6.4.1 and Figure 6.4), the computations based on snow depth would lead to conclude that on average the season duration decreases when grooming of 9 days (Northern Alps) to 13 days (Southern Alps) with a maximum difference at an elevation of 900 and 1200 m.a.s.l in the Northern Alps (15 days) and 1500 m.a.s.l in the Southern Alps (22 days). In case the reliability is addressed from snow depth thresholds, this suggests that the suitable conditions for skiing are depreciated by grooming, which is a major misinterpretation. The calculation based on SWE provides more consistent data between groomed and natural snow conditions (no large differences) and suggests that the season duration is lengthened by grooming as reported in the literature (Rixen et al., 2004; Keller et al., 2004; Spandre et al., 2016c) leading to the opposite conclusion compared to the calculation based on snow depth. Any investigation of the vulnerability of snow related economy accounting for snow grooming and snowmaking with the related impacts on snow properties should therefore not use any calculation (season duration, viability index) based on snow depth but use snow mass instead, especially when comparisons are made between natural and managed snow conditions.

6.5.4 Underestimation of the total water volume used for snowmaking

The total water consumption for snowmaking in France was estimated by ODIT (2009); Badré et al. (2009) from records of the annual informations provided by ski resorts, from 1995 (6 Mm³, 7% of equipped ski slopes with snowmaking facilities) until 2007 (18.9 Mm³, 20% of equipped ski slopes). Badré et al. (2009) warned that these informations are based on volunteer communication from ski resorts and that ODIT (2009) had filled the missing values by extrapolating the information from the participant ski resorts (one third of them), although no publication explicitly described the method that has been used. The French Alps ski resorts represent 84% of the national ski slopes surface area and 84% of ski lifts facilities (ODIT, 2009). Since our sample of 129 ski resorts represents 96% of French Alps ski lifts infrastructures, we assumed the sample also represents an approximate 96% of French Alps ski slopes surface area i.e. 80.6% of the national ski slopes surface area. Assuming our sample of ski resort is representative of the French ski resorts in terms of snowmaking (Spandre et al., 2016a), we estimated the total water consumption of the 129 ski resorts sample to be 80.6% of the national record of water consumption (Badré et al., 2009) i.e. 4.8 Mm³ in 1995 and 15.2 Mm³ in 2007. Badré et al. (2009) concluded the water consumption per hectare of ski slope equipped with snowmaking facilities was steady between 1995 and 2007 with 3500 m³ ha⁻¹. These data suggest that our method underestimates the total amount of water used for snowmaking : the water consumption per hectare from Badré et al. (2009) showed a factor 1.75 with the results from our simulations (3500 versus 1982 m³ ha⁻¹). The deviation is even more important for the simulated total amount over the periods 1994 - 1996 (2.6 Mm³ versus 4.8 Mm³) and 2006 - 2008 (5.7 Mm³ versus 15.2 Mm³) i.e. a factor 1.8 to 2.7. We expect such differences to be due to three main reasons.

First, ski resorts may produce more snow than we actually simulated (target of 150 kg m⁻² before the 15 December and until a 60 cm total snow depth afterwards). Although our approach is consistent with the literature (Scott and McBoyle, 2007; Steiger, 2010; Hanzer et al., 2014) and in particular with

a recent survey of French ski resorts (Spandre et al., 2016a), the actual practices of ski resorts may be to produce more snow than what was considered in our study.

Second, we did not account for the water losses occurring during the snowmaking process with a significant fraction of the water volume used for snowmaking that may be lost (Eisel et al., 1988, 1990; Olefs et al., 2010; Spandre et al., 2016b). Hanzer et al. (2014) implemented the relationship derived by Eisel et al. (1988) and estimated that for typical production temperatures, the water losses due to thermodynamic processes (evaporation and sublimation) ranged between 2 and 13% of the water volume. However thermodynamic processes alone can not explain the water losses reported by Eisel et al. (1990) with an additional 7 to 33% losses computed from the difference between the observations and the simulations of runoffs in six test sites in Colorado. Similarly Spandre et al. (2016c) calculated water losses from observations of four test sites in the French Alps compared to simulations with a minimum 25% water losses, up to 50%, while Olefs et al. (2010) addressed such losses from interviews with professional snowmakers with 15 to 40% losses for air water guns (the majority of snowguns in France). Last, Spandre et al. (2016b) realized observations using a GPS method on MM snow piles and later on the ski slope opened to skiers and estimated a 40% water loss under ideal conditions for production. All investigations outline that water losses are site and conditions dependent, hampering to derive a single value. However it is very likely that a significant fraction of the water volume is lost which may partially explain the difference in the water amount per hectare of equipped ski slope. If accounting for a 30% water loss, the required amount of water per hectare of equipped ski slope to provide the same snow conditions as simulated in the present study would be $2831 \text{ m}^3 \text{ ha}^{-1}$ i.e. only 19% below the data from Badré et al. (2009).

Beyond the amount of water per hectare of ski slope, the total surface area of equipped ski slopes also differ between ODIT (2009) and the present study, leading to an additional underestimation of the total water consumption derived here. ODIT (2009) reported an envelope surface of French Alps ski resorts (p. 42) of 132 600 ha within which the ski slopes would cover 22 284 ha in 2007 - 2008 resulting in a ratio of 0.17 significantly higher than the one we used (0.11). ODIT (2009) did not publish any method on how they derived such values and did not evaluate the uncertainty of their results which is a difficulty to discuss this issue. However, assuming our sample of 129 ski resorts represents an approximate 96% of French Alps ski slopes surface area, we estimated the ski slopes surface area from ODIT (2009) corresponding to our sample of ski resorts to be 21 393 ha. The total ski slopes surface area of the sample ski resorts in the present study represents 16 133 ha compared to the 21 393 ha from ODIT (2009) i.e. a 24.5% difference. The differences between the surface areas equipped with snowmaking facilities for a given ratio are identical. Therefore when aggregating over the whole French Alps, the total amount of water would remain 24.5% lower even if the required water per hectare of ski slope was identical.

To conclude, even though ski resorts may actually produce more snow than simulated in the present study, we provided three objective reasons which might explain the differences in the total water consumption for snowmaking. Both water losses which are not taken into account in the present study and the estimate of the surface of ski slopes lead to an underestimation of the total water amount required for MM snow production. Accounting for a 30% water losses ratio and for the 24.5% difference between the ski slope surface estimated by ODIT (2009) and in the present study, we obtain a 4.8 Mm^3 over the periods 1994 - 1996 versus 4.8 Mm^3 and 10.8 Mm^3 over the 2006 - 2008 period versus 15.2 Mm^3 i.e. a factor limited to 1 and 1.4 between our simulations and the data from Badré et al. (2009) and ODIT (2009). As a consequence, it is likely that the associated energy consumption is also underestimated by our method in the same proportions, although the assumption of a constant

energetic efficiency of snow guns over the 1985 - 2014 is questionable.

6.6 Conclusion and outlooks

An original approach was introduced for the investigation of socio economic implications of changes in snow conditions for the French Alps ski resorts. This approach was based on objective features of ski resorts (ski lifts, size, elevation) to provide an integrated model which explicitly accounts for the physical impacts of snow management and detailed locations of ski resorts. The snow reliability line (SRL) elevation was computed based on the snow conditions simulated for the 1958 - 2014 period and the application of the "100 days" rule. The SRL elevation based on groomed snow conditions was found significantly higher compared with previous investigations by Abegg et al. (2007) with an average elevation of snow reliable conditions of 1480 m.a.s.l in the Northern Alps and 2035 m.a.s.l in the Southern Alps. This resulted in 20% of French Alps ski resorts which would be snow reliable at the elevation of the village and 63% at the average elevation of ski lifts for the 1958 - 2014 period, according to the SRL approach. Accounting for snowmaking, 91% of French Alps ski resorts would be snow reliable at the village elevation and 127 out of the 129 (98%) at the average ski lifts elevation.

Alternative snow reliability indicators were computed for the 1958 - 2014 period and correlated with the ski lifts tickets sales (skier days) on the 2001 - 2014 period. A combined indicator of the viability index of the Christmas and New Year holidays with the Winter school holidays showed the best correlation with the skier days, including the capacity to capture the rate of variation of skier days with respect to changes in snow conditions. This "combined holidays" viability index was obtained for a relative weight of Christmas and New-Year holidays of 16 to 22% versus 78 to 84% for the Winter school holidays. This index revealed a significant variability of snow conditions between resorts categories and French massifs, with a significant spatial gradient from the North to the South of French Alps (Section 6.4.5). The location of a ski resort therefore confirmed to be a major discriminating factor for its vulnerability to snow conditions, with a significant additional effect related to its size (Table 6.7).

This method proved its ability to produce relevant indicators of the reliability of snow in ski resorts accounting for spatial representations of surfaces equipped with snowmaking facilities in ski areas. The highest elevation of snowguns was significantly correlated with the average elevation of ski resorts consistently with Spandre et al. (2015) and the rate of variation of skier days was found to be best captured by a 15 to 30% ski slopes equipped with snowmaking facilities, consistently with the observed ratio on the 2001 - 2014 period (Hahn, 2004; Spandre et al., 2015). The snowmaking requirements were aggregated for all French Alps ski resorts and compared with records of water volumes used for snowmaking from 1995 to 2007 (Badré et al., 2009). These computations revealed that the major driver of the increase of water and energy requirements for snowmaking purposes was the significant increase from 1985 to 2014 of the surface area of ski slopes equipped with snowmaking facilities. However, we showed our approach would under estimate the ski slopes surface area by 24.5% compared to estimations by ODIT (2009) and the amount of water per hectare of ski slopes by a factor 1.75. This difference in the amount of water per hectare of ski slopes may be partially explained by the water losses occurring during the snowmaking process which we did not take into account in the present study. These results might be considered as an additional proof that such water losses may be significant (Spandre et al., 2016b).

Finally, this original approach provided relevant information for socio economic investigations of the activity of French Alps ski resorts including the assessment of the vulnerability of the ski industry to snow conditions and the water and energy requirements for snowmaking purposes under past climate

conditions. We therefore expect to use this method on all French massifs outside the Alps where SAFRAN meteorological forcing data are available as well as structural data on ski lifts facilities although not yet integrated in the “BD Stations”. We also consider this approach could be further used for prospective investigations of interactions between snow conditions and human activities in ski resorts, considering hypothetical evolutions of the climate and/or of snowmaking facilities to assess the economic implications and water and energy additional requirements related to such changes.

Conclusion and Outlooks

Interactions The investigations developed during the course of this PhD focused on the interactions between snow conditions (variability, low predictability) and human activities (goals, means and perceptions) in ski resorts. Complementary approaches were integrated into an original modelling approach including a physically based snowpack model, comprehensive and explicit approaches of snowmaking and grooming on snow properties, spatial representations of ski slopes for the entire French Alps and detailed elements on snow management operations by ski resorts stakeholders. The development and evaluation of this modelling chain was described in the present work by means of a survey of French ski resorts, discussions and field observations, sensitivity tests, literature and retrospective analysis. Hereafter is an overview of this work, its major limitations as well as suggestions for further investigations of these questions.

A picture of snow management operations

In a first step of this PhD, the objectives pursued by operators, the means they employ (grooming, snowmaking) and constraints they face (meteorological, structural or organization issues) in daily operations have been investigated to provide a synthesis of snow management operations in French ski resorts which can be used for modelling purposes (chapters 2 and 3). A survey was set up and collected data from 55 French ski resorts, representing 25% of the national ski resorts and 50% of the national ski lifts infrastructures. Our survey showed that all resorts shared most operational priorities, particularly regarding the satisfaction of skiers through comfortable skiing conditions and to guarantee to ski back down to the village. A snow depth of 40 to 50 cm appeared to be the minimum required snow depth to provide satisfying skiing conditions. The grooming of ski slopes was originally used to guarantee the suitable conditions expected by both the skiers and the ski resorts operators as long as there was sufficient natural snow. Snowmaking was further considered as the most efficient way to compensate the lack of natural snow and Medium to Very Large resorts equipped about 35% of their ski slopes with snowmaking facilities between 1985 and 2015. This ratio increased very quickly from the 1990s and was expected to reach 40% of equipped ski tracks in 2020. Even though the Medium to Very Large resorts were equipped at similar levels in 2015, the Very Large resorts should be the most equipped resorts in 2020 (about 50% of their ski tracks surface), followed by the Large (41%) and the Medium resorts (41%). The capacity of the dedicated reservoirs to snowmaking with respect to the surface of equipped ski slopes represented an equivalent 150 to 190 liters (kg) of water per m^2 (i.e. 38 to 48 cm of machine made snow assuming a density of 400 kg m^{-3}).

Spandre et al. (2016a) showed from sub samples of ski resorts that the ratio of equipped slopes with snowmaking facilities was correlated with the viability index to natural snow conditions computed by François et al. (2014) of these sub samples. This suggested that the natural snow conditions influenced the level of equipment of ski resorts even though this was probably not the final decision maker but an

influential factor among many others. Beyond similar approaches of the snow management between ski resorts regardless their main features, our survey actually highlighted the greater adaptive capacity of Large and Very Large French ski resorts, particularly regarding the recent development of snowmaking. On one hand, Small to Medium resorts benefit from poorer natural snow conditions mainly due to lower elevations of resorts (François et al., 2014) and may not have the possibility to invest in snowmaking facilities or with uncertain contribution to their operations. Snowmaking potentials at low elevations were computed in the French Alps for the 1961 - 2014 period and were significantly lower than for higher elevations, above 1800 m.a.s.l. A decline of these potentials was shown at all elevations with several statistically significant cases. On the other hand, Large and Very Large resorts are located in higher elevations, benefiting from better natural snow conditions and invest in extensive snowmaking facilities with higher snowmaking potentials, turning snowmaking as a sales pitch (“Snow guarantee”) and into a proof of the anticipation of climate change future challenges. The chapters 2 and 3 therefore revealed structural elements on snow management processes in French ski resorts and provided an analysis of the adaptive capacity of resorts. This made possible the integration of grooming and snowmaking operations into a snowpack model capable of large scale modelling of snow and meteorological conditions and the analysis of the simulated snow conditions thanks to these contextual elements provided by the survey.

Modelling physical impacts on snow properties

A physically based modelling approach of the impact of grooming and snowmaking on snow properties was developed in the snow model Crocus and evaluated with respect to field observations over two consecutive winter seasons (chapters 4 and 5). Comprehensive grooming and snowmaking approaches have been implemented in Crocus, based on the literature and interviews with professionals. The effect of the tiller was explicitly taken into account. The snow properties (density, snow microstructure) are homogenized and modified, in addition to the compaction induced by the static weight of the grooming machine. The grooming model was proven to yield realistic simulations of groomed ski slopes with respect to observations (snow depth, snow water equivalent and stratigraphy), more efficiently than natural snow or even static load approach. The impact of grooming on the thermal regime of the ground under a snow cover was recorded during six months in Autrans by temperature loggers. The periods with soil frost were consistent with the observations, confirming that grooming strongly enhances the fraction of time when soil is frozen (20% under natural snow versus 70% under groomed snow). The average temperatures were significantly lower under a groomed snowpack, similarly to findings from Rixen et al. (2004) which was consistently simulated.

Regarding snowmaking, the specific properties of MM snow (density, specific surface area, sphericity) were taken into account in the model. The observed history of production was collected for every observation site and implemented as the production target. The snowmaking model provided realistic simulations of the snowpack properties with respect to observations, to the specified rules and to the current meteorological conditions. The main uncertainty pertained to the efficiency of snowmaking processes i.e. the amount of water used for snowmaking which can actually be recovered as machine made snow on the ski slope. The best agreement between observations and simulations was found in 2014 - 2015 for an efficiency ratio R of 50% to 75% in Tignes, 50% to 25% in Les 2 Alpes, 25% to 50% in Chamrousse and Autrans, which was significantly lower than expected from the literature. Overall the development of Crocus - Resort appeared satisfying in terms of impact of the management of snow on the snowpack properties although confirming that water losses are a major concern which is probably less due to the modelling approach but more importantly to the snowmaking process itself.

Assessing the efficiency of the snowmaking process

Eisel et al. (1988, 1990) provided the most detailed investigations of water losses during the snowmaking process, showing that water losses during snowmaking could not be satisfyingly limited to evaporation and sublimation alone. We provided spatial observations in Les Deux Alpes ski resort (French Alps) of the snow depth and snow water equivalent of MM snow piles and of the ski slope as opened to skiers using an original approach based on a Differential Global Navigation Satellite System (GNSS). The observations of single sessions of production (five observations) showed similar distributions around the center of the MM snow pile with approximately 30% of the water mass recovered as machine made snow within 10 m and 50% within 20 m. The water recovery rate (WRR) within the ski slope edge was computed in three occasions with approximately 60% ($\pm 10\%$) of the water mass used for snowmaking recovered as MM snow. The water losses due to thermodynamic effects (evaporation, sublimation) were calculated from Eisel et al. (1988) linear approximation which showed that a significant fraction of the water used for snowmaking probably turned to MM snow but could not be recovered within the edge of the ski slope. We concluded that the water recovery rate of the snowmaking process was a tricky question regarding its likely dependence to both sites characteristics (topography, vegetation) and human decisions (attention to marginal conditions, quality parameter, etc.). Estimating a single value appeared impossible even though the best conditions together (as could be considered these observations) showed that a significant fraction of the water used for production was lost for the ski slope. An objective reason for the loss of water was identified as the local topography : less than 50% of the water mass was observed within the edge of a typical ski slope width (approximately 20 to 30 m) with snowguns on the side and perpendicular to the slope (a typical installation). These observations therefore attempted to improve our understanding of water losses during the snowmaking process and concluded that additional investigations were required, particularly regarding the human decisions taken when producing snow. This issue remains a major concern and questions the relevance of snowmaking as a mitigation method of the impacts of the climate variability and projected changes. Significant water losses may have strong economical impacts on the interest of snowmaking for the operation of ski resorts.

Integration and upscaling

The structural elements on snow management operations in French ski resorts and the physically based snowpack model accounting for snow grooming and snowmaking were crossed with a socio economic database of ski resorts to provide an explicit spatial modelling of managed snow conditions on ski slopes for the entire French Alps ski resorts. Such method allowed defining snow reliability indicators which relevance and reliability were discussed in a retrospective analysis on the 1958 - 2014 period (chapter 6). The snow reliability line (SRL) elevation was computed based on the snow conditions simulated for the 1958 - 2014 period and the application of the "100 days" rule. About 20% of French Alps ski resorts would be snow reliable at the elevation of the village and 63% at the average elevation of ski lifts for the 1958 - 2014 period, based on natural snow conditions. Accounting for snowmaking, 94% of French Alps ski resorts would be snow reliable at the village elevation and 128 out of the 130 (98.5%) at the ski lifts average elevation. Alternatively a combined indicator of the viability index of the Christmas and New Year holidays with the Winter school holidays showed the best correlation with the skier days, including the capacity to capture the rate of variation of skier days with respect to changes in snow conditions. This index confirmed a significant variability of snow conditions between resorts categories and French massifs, with a significant spatial gradient from the North to the South

of French Alps. The snowmaking requirements were aggregated for all French Alps ski resorts and compared with records of water volumes used for snowmaking from 1995 to 2007 (Badré et al., 2009). We showed that our approach would underestimate the total water volume by a factor 1.8 to 2.7. The differences might be explained by an underestimation of the total ski slopes surface area and of the amount of water used for snowmaking per hectare of ski slopes. The latter may be related to the water losses during the snowmaking process which were not take into account. Overall, this original approach provided relevant information for socio economic investigations of the activity of French Alps ski resorts including the assessment of the vulnerability of the ski industry to snow conditions and the water and energy requirements for snowmaking purposes under past climate conditions.

Shortcomings and outlooks related to the present work

All constitutive elements of the modelling chain described in the present PhD work are based either on assumptions or frameworks which could or should be improved. This includes the human operations of snow management (grooming, snowmaking), the physical impacts of these methods on snow properties, the understanding of the interactions between touristic and industrial activities with the snow conditions and the role played by climate changes in the evolution of these interactions. Here is an overview of the major shortcomings of the present work.

Limitations regarding the assessment of snow management operations. The sample of ski resorts of our survey may be considered as representative of medium to very large resorts (about 50% in number and ski lift power of the national total). Regarding Small resorts, only four participated while there are about 130 ski resorts (DSF, 2011), hampering any generalization of the results for this category. Additionnally, we showed that the recent developments in snowmaking facilities appeared highly individualistic and in a large extent independent to the vulnerability of ski resorts to snow conditions. We hypothesized that this could be related to the target market of ski resorts (local or even domestic versus international customers). The flexibility of visitors, their present and future perception of snowmaking and way of consuming (through tour-operators, last minute bookings, day trippers, etc.) certainly result in contrasted demands for snow guarantees and the related developments of snowmaking facilities.

Suggestions

- Since Small resorts are likely to be the most vulnerable to snow scarcity, additional investigations on this specific category are strongly needed ;
- Further investigations would be necessary in order to profile ski resorts beyond the size and location, including as a first priority the target market and the distance to the closest urban area. This could also be done by correlating the overnight stays with ski lifts tickets sales (see next point) ;

Limitations regarding economic indicators. The present work considered the ski lifts tickets sales (skier days) as the reference indicator of the economic success of a ski resort, a category of resorts or a winter season. This is a major shortcoming since this approach does not consider the share of the skier days revenue into profit and loss. Since our approach allows computing the evolution of e.g. water volumes and energy requirements for snowmaking, it would be highly relevant to convert these into an evolution of running charges for ski resorts. Skier days can not differentiate distinct management modes of ski resorts. Resorts operators may manage the real estate offer which makes the skier days a fraction

of the revenue with overnight stays in the resort or the sales of real estate. Similarly ski resorts owned by host communities may have distinct business models than those which are privately owned (merging with the limitations in snow management operations above). Addressing these limitations would require further investigations of economic indicators to account for ski resorts specific features.

Suggestions

- Economic indicators could be used alternatively to skier days as described, for example, by Töglhofer et al. (2011) in Austria (overnight stays) and more recently Falk and Vanat (2016) in France (investments, sales revenues, employment, number of persons transported uphill, skier visits);
- The management mode (privately owned, semi-public or public) of ski resorts should be explicitly considered;

Limitations in the spatial representations of ski slopes. The spatial representations of ski slopes were originally developed by François et al. (2014), improved by Francois et al. (2016) and snowmaking envelopes were created in the present work. Assessing the ski area from ski lifts infrastructures is an objective approach which can be applied for all French ski resorts since ski lifts must be declared to a specific national service (STRMTG). This is a major strength of the method. However, the ratio of the ski resort surface area from this method and the actual ski slopes surface area showed a standard deviation value of 36% of the average ratio, resulting in a relatively large uncertainty when, for example, computing the water volumes required for snowmaking. Another limitation is the spatial resolution of the Digital Elevation Model used for the present study (625 m² pixels), particularly regarding the slope angle of pixels. In order to provide consistent representations of gravitational envelopes (spatial continuity), the maximum angles admitted in the present study for skiing (45°) and for the easiest slopes (25°) exceed the actual angles of ski slopes. Additional evaluations and developments may improve this method and reduce the related uncertainties.

Suggestions

- Spatial representations of the ski slopes (gravitational envelopes) and snowmaking envelopes could be addressed to the largest possible panel of ski resorts to have an individual feedback from resorts stakeholders on the relevance of these representations;
- An elevation model of the ground with a higher resolution may improve the accuracy of the method;

Limitations in the modelling of snow. The main uncertainty in the snowpack model pertains to the efficiency of the snowmaking process. Although this depends more on the process itself, this is a major limitation of the modelling of snowmaking which requires further investigations, particularly regarding the influence of meteorological conditions (wind, temperature) and the vegetation at the considered sites. Additionally, we showed that the melting rate on the ski slope was lower in the model compared to observations. We hypothesized that the impurities contained in the water stored in open reservoirs may have a significant impact on the melting rate of the machine made snow. Regarding the local sources of black carbon in ski resorts (engines traffic, human activities), the deposition of impurities may also be significantly higher in ski resorts than in wild areas. Similarly, the snow-ground partitioning is hypothesized to be a major shortcoming of the current modelling approach of managed snow on ski slopes, particularly when the natural snow melts out and leaves the ski slope as an isolated snow patch in grass/rock fields.

Suggestions

- Water losses should be considered in any further investigations. Impact studies should not neglect these losses any more ;
- Observations of the snowmaking efficiency with different types of snowguns and “Quality” parameterization are strongly needed ;
- The remaining liquid water in machine made snow piles after the production may be taken into account in the model ;
- Observations of impurities content and deposition on the snow in ski resorts would be highly relevant ;
- The impact of snow and bare ground partitioning on turbulent fluxes may be a relevant improvement of the snow model ;

Limitations in using numerical models. The interactions between natural systems with human activities depend on a wide range of influential factors with contrasted objectivity, diversity and potential for modelling approaches. As members of the scientific community we should remain aware of the rising interest for numerical models. Obvious interests (computational capacities) and opportunities (community based projects) were made possible thanks to such approaches. Necessarily, weaknesses and threats appeared too. I suppose the complexity of numerical models based on community projects can not be handled by single persons with a significant probability to ignore the impacts of others work on one’s own results. The constant evolution of community models may also harm their capacity to reproduce results (outdated versions, incompatibility, non reversible evolutions). The difficulty to model some factors (human decisions, systems with multiple dependences) may encourage the scientist to neglect these factors by using coarse assumptions or approaches, whose impacts on simulations results should be carefully evaluated. Since modelling structures, coding and integrations are increasingly complex, the development may concentrate the dedication of the scientist and hide major concerns related to the relevance of assumptions (inputs) and the importance of evaluating the results (outputs). A complex modelling approach of a poorly understood system can not provide relevant and reliable information. In particular, human decisions and strategies may be highly subjective, may not be summarized in a systematic and single approach and proved to be of major interest regarding snow management (habits, expertise). In addition, this is a dynamic factor since the perception of resorts stakeholders of climate changes and related consequences (for example) may change in time.

Suggestions

- Regarding snow physics and geosciences in general, the observations provide contextual elements (uncertainties) and some expertise for the evaluation of model results. Observations should not be neglected in the research on snow in favor of numerical models developments ;
- The understanding of human decisions and perceptions of resorts stakeholders of climate changes and projected consequences need significantly deeper investigations ;

Applications (Outlooks) The previous discussion points provided a few suggestions and outlooks to improve the modelling approach described in the present work. Actually, this method already proved its ability to provide relevant and reliable information for socio economic investigations of the activity of French Alps ski resorts, explicitly accounting for the physical impacts of snowmaking and grooming on snow properties, detailed snow management operations in ski resorts and spatial representations of ski slopes including snowmaking distribution within ski resorts. This integrated modelling approach was used for a retrospective investigation of the vulnerability of the French Alps ski industry to snow conditions and the computation of water and energy requirements for snowmaking purposes during the

1958 - 2014 period. This confirmed the relevance of both snow reliability indicators and snowmaking requirements, suggesting that this method may be used for further investigations.

Firstly this could be applied on all French massifs outside the Alps where SAFRAN meteorological forcing data are available as well as structural data on ski lifts facilities.

Secondly we consider that this approach could also be used for prospective investigations considering hypothetical evolutions of the climate and/or of snowmaking facilities to assess the economic implications and water and energy additional requirements related to such changes.

At last, referring to my initial example of the investment plan in snowmaking facilities in the "Auvergne Rhône-Alpes" region, political decisions may result and benefit from even more fruitful debates if based on such objective information. Overall, our approach may reduce the uncertainty in the perception of climate induced challenges by policy makers and resorts stakeholders. Hopefully this may lead to improved choices and enhanced attention to the substantial concerns regarding the development of mountain regions. In return, this may intensify the curiosity of representatives and resorts operators for such research projects as we already experienced during the course of this PhD. Such curiosity would not only help in every day developments e.g. designing relevant snow and economic indicators but more importantly would confirm and strengthen the interest for such integrated and multidisciplinary research projects.

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Peer-reviewed (avec comité de relecture)

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- **Spandre P.**, François, H., Thibert E., Morin S., George-Marcelpoil, E., 2016. Determination of snowmaking efficiency on a ski slope from observations and modelling of snowmaking events and seasonal snow accumulation. The Cryosphere Discussion, doi :10.5194/tc-2016-194
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- **Spandre P.**, Morin S., George-Marcelpoil E., Lafaysse M., François H., 2016. “Observation et modélisation des conditions d’enneigement dans les domaines skiables” Journées R&D Météo-France, Toulouse, June 2016. Talk.
- **Spandre P.**, François H., Morin S., George-Marcelpoil E., “Observation et modélisation de l’organisation structurelle et des impacts physiques de la gestion de la neige dans les domaines skiables français” Conseil Scientifique du Parc National de la Vanoise, Val Thorens, June 2016. Talk.
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