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1 Integration of snow management processes
2 into a detailed snowpack model

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7 **Abstract**

8 The understanding and implementation of snow management in detailed snowpack
9 models is a major step towards a more realistic assessment of the evolution of snow
10 conditions in ski resorts concerning past, present and future climate conditions. Here
11 we describe in a detailed manner the integration of snow management processes
12 (grooming, snowmaking) into the snowpack model Crocus. The effect of the tiller
13 is explicitly taken into account and its effects on snow properties (density, snow
14 microstructure) are simulated in addition to the compaction induced by the weight of
15 the grooming machine. The production of snow in Crocus is carried out with respect
16 to specific rules and current meteorological conditions. Model configurations and
17 results are described in detail through sensitivity tests of the model of all parameters
18 related to snow management processes. In-situ observations were carried out in
19 four resorts in the French Alps during the 2014-2015 winter season considering for
20 each resort natural, groomed only and groomed plus snowmaking conditions. The
21 model provides realistic simulations of the snowpack properties with respect to these
22 observations. The main uncertainty pertains to the efficiency of the snowmaking
23 process. The observed ratio between the mass of machine-made snow on ski slopes
24 and the water mass used for production was found to be lower than was expected
25 from the literature, in every resort.

26 Nevertheless, the model now referred to as "Crocus-Resort" has been proven to
27 provide realistic simulations of snow conditions on ski slopes and may be used for
28 further investigations.

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29 *Keywords:* Snow management, grooming, snowmaking, snowpack modelling,
30 French Alps, Ski resorts

31 **1. INTRODUCTION**

32 The management of snow on ski slopes is a key socio-economic and environ-
33 mental issue in mountain regions. Indeed, the winter sports industry has become
34 a very competitive global market (Agrawala et al., 2007). Ski lift operators face
35 multiple expectations from both consumers and investors (Fauve et al., 2002; DSF,
36 2014) such as ensuring opening/closing dates and maintaining safe and homoge-
37 neous conditions, etc. Further to operating costs (Damm et al., 2014), the increasing
38 attention paid to environmental issues (Steiger, 2010; Magnier, 2013) arouses the
39 interest of both policy makers and ski lift operators concerning optimization levers
40 of energy and water consumption and for reliable data concerning the ability of the
41 snow industry to face climate challenges (Scott and McBoyle, 2007).

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

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

82 Nevertheless, the effects of snow management on snowpack properties are still
83 rarely described in literature and only a few studies have reported detailed field
84 observations (Keddy et al., 1979; Guily, 1991; Keller et al., 2004; Howard and Stull,
85 2014). In order to build a tool capable of addressing snow conditions on ski slopes
86 for a wide range of resorts we have explicitly integrated comprehensive grooming
87 and snowmaking approaches into the detailed multi-layer snowpack model Crocus
88 (Vionnet et al., 2012). Grooming and snowmaking were implemented in Crocus

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 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).

89 based on our physical comprehension of processes, literature and interviews with
90 professionals. The latter were involved in our development strategy to represent
91 their management practices in the most consistent way, which is critical for any
92 further use of such a model. The model was evaluated with field measurements
93 (depth, snow water equivalent and vertical profiles) carried out in four resorts in
94 the French Alps during the 2014-2015 winter season. These measurements and
95 the model implementation are described in an extensive manner including decision
96 schemes and model parameterization. Instead of integrating in detail the specific
97 snow management practices of one particular ski resort (Hanzer et al., 2014), this
98 development aims to build a tool able to simulate the snow conditions for a wide
99 range of resorts and geographical areas (François et al., 2014), and thus requires a
100 rather generic formulation if possible. We tested the sensitivity of the model to the
101 values of parameters and evaluated the results of simulations with respect to in-situ
102 observations.

103 2. MATERIAL AND METHODS

104 2.1. *In-Situ observations*

105 Ski patrols from four specific resorts located in the Northern French Alps (Tignes,
106 Chamrousse, Autrans and Les 2 Alpes) helped us to perform measurements during
107 the 2014-2015 winter season (Table 1, Figure 1), covering a large range of meteo-
108 rological conditions and operators' habits and means.

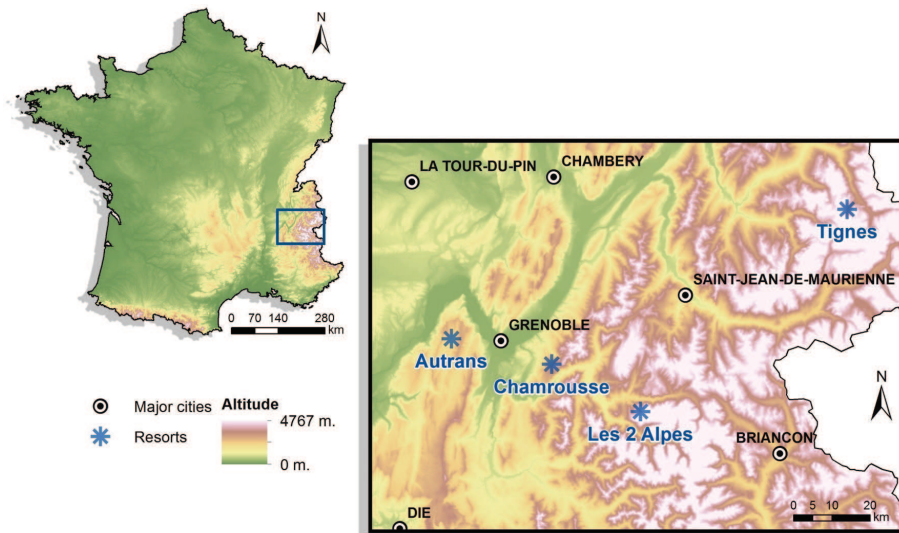


FIGURE 1: Location of the ski resorts around the city of Grenoble (France) : Tignes (Haute-Tarentaise), Chamrousse (Belledonne), Autrans (Vercors) and Les 2 Alpes (Oisans).

109 *2.1.1. Observations Sites*

110 Three observation sites with natural snow conditions (Reference site), grooming
 111 and packed and skied snow conditions (Site G) and grooming plus snowmaking and
 112 skiing (Site SM) were chosen in each resort with the aid of ski patrollers. All three
 113 sites within a given ski resort are located as closely as possible to each other and
 114 are easy to access. In every case local topography consists of flat or almost flat
 115 areas with as little wind disturbance as possible. None of the sites are in erosion or
 116 accumulation areas. However all sites are located in mountain areas where the wind
 117 may always play a significant role and be a factor of uncertainty.

118 *2.1.2. Snowmaking data on SM sites*

119 The most likely surface on which MM snow was spread (S_{mid}) was calculated
 120 from ski slope edges, snow gun distribution on the ski slope, in-situ observations
 121 and interviews with professionals. For example in Tignes, snow guns are equally
 122 distributed on “Double M” ski slopes and the distance between them is 67 m.
 123 The width of the site SM is 36 m, resulting in a 2400 m² surface. Assuming an

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 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.

124 uncertainty of $\pm 400 \text{ m}^2$ i.e. $\pm 17\%$ on the surface (an uncertainty of about 8%
125 concerning length and width), the resulting range on the surface is S_{min}=2000 to
126 S_{max}=2800 m² (the minimum and maximum surfaces on which MM snow could
127 have been spread respectively). Similar treatments were applied in other resorts
128 (Table 2).

129 The uncertainty on spreading surfaces is shown in figures (section 5) as an
130 envelope (corresponding to simulations using S_{min} and S_{max}) around the standard
131 simulation (which uses S_{mid}).

132 2.1.3. Measurements

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

- 135 – Snow depth (SD) was measured once a week by ski patrollers, on each site.
136 Depending on local topography several measurements were made for each
137 site so as to provide reliable integrated results as well as an indication of the
138 deviation of measurements.
- 139 – The average density of the snowpack was measured once a month on each
140 site. We used a Polar Ice Coring Office (PICO) lightweight coring auger (Koci
141 and Kuivinen, 1984).
- 142 – The snow water equivalent of the snowpack was deduced from these obser-
143 vations, as the product of SD and average density .
- 144 – A complete stratigraphy of the main site SM with grooming and snowmaking

145 was carried out every month. It included the measurement of snow layers
146 specific surface areas (SSA), using the DUFISSS instrument (Gallet et al.,
147 2009; Morin et al., 2013) and snow layers density (Fierz et al., 2009).
148 Average observations are displayed as dots on results figures (section 3, 4 and
149 5) with a surrounding envelope corresponding to \pm the standard deviation of the
150 observations.

151 2.2. SAFRAN - Crocus model chain

152 2.2.1. Snowpack Model

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

- 164 – Density (ρ) : the mass of a snow sample per unit volume (Vionnet et al.,
165 2012) ;
- 166 – Specific surface area (SSA) : the total area at the ice/air interface in a snow
167 sample per unit mass (Carmagnola et al., 2014) ;
- 168 – Sphericity (S) : the ratio between rounded versus angular shapes (Brun et al.,
169 1992) ;
- 170 – Age : the time since snowfall, used to approximate the radiative impact of the
171 deposition of light-absorbing impurities on the snow (Vionnet et al., 2012)
172 snowpack properties (Figure 2), including grooming and snowmaking processes.

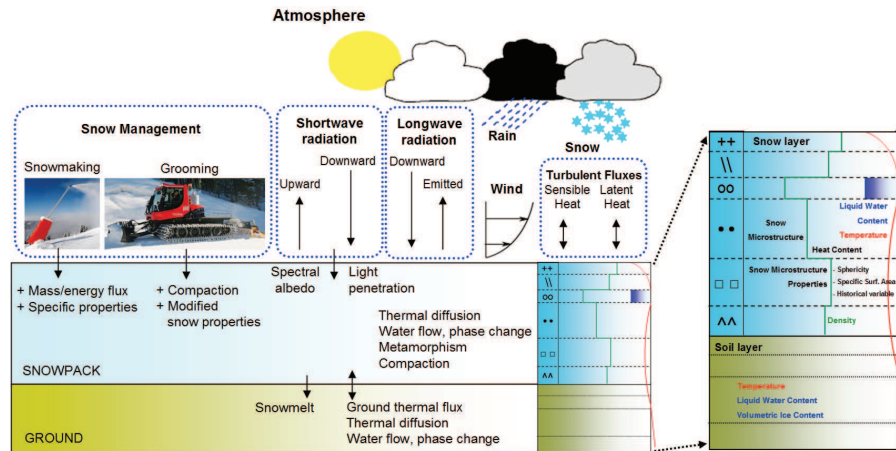


FIGURE 2: The SAFRAN-SURFEX/ISBA-Crocus scheme including grooming and snowmaking effects on snowpack physics, adapted from Vionnet et al. (2012).

173 2.2.2. Meteorological Data

174 In French mountain regions, Crocus is usually run using outputs of the meteo-
 175 rological downscaling and surface analysis tool SAFRAN (Durand et al., 1993). SA-
 176 FRAN operates on a geographical scale on meteorologically homogeneous mountain
 177 ranges (referred to as “massifs”) within which meteorological conditions are assu-
 178 med to depend only on altitude and slope aspect. There is strong evidence from
 179 operational and research activities that the SAFRAN-Crocus model chain yields rea-
 180 listic results in French mountain regions in terms of integrated snow properties such
 181 as snow depth and snow water equivalent (Lafaysse et al., 2013). For a detailed re-
 182 view of know applications of SAFRAN-Crocus since its original development, please
 183 refer to Vionnet et al. (2012) and to the page “Crocus- Scientific applications”
 184 (www.cnrm-game.fr web site).

185 All simulations in this paper are based on meteorological forcing data from SA-
 186 FRAN corresponding to each site (altitude, slope angle and aspect). We specifically
 187 analysed the natural snow conditions provided by SAFRAN-Crocus with in-situ ob-
 188 servations on a local scale from ski patrollers and Automatic Weather Stations
 189 (wind, snow/rain altitude limit, precipitation amount). We fitted the SAFRAN me-
 190 teorological forcing data to local conditions for each observation site. Precipitation



FIGURE 3: 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

191 amount and phase were modified for several precipitation events on each site :
192 Tignes (2 modified events), Chamrousse (4), Autrans (3) and Les 2 Alpes (6). All
193 other meteorological variables remained unchanged.

194 We also took into account the surrounding slopes of each site and the consequent
195 shadowing effect (Morin et al., 2012). We used a 25 m digital elevation model
196 (Marcelpoil et al., 2012) to create a skyline profile : for each azimuth (steps of
197 10°), the elevation angle of the visible sky was calculated and checked with in-situ
198 measurements.

199 2.3. Grooming approach in the snowpack model

200 Our approach to artificial snow grooming consists of both an extra static load
201 applied on the snowpack and the additional effects of the tiller applied simulta-
202 neously.

203 2.3.1. Static Stress

204 The natural densification of the snowpack layers is mostly driven in the model
205 by the weight of the top layers applied to those which are deeper (Vionnet et al.,
206 2012). The static stress applied on the snowpack due to the weight of a grooming
207 machine (ranging from 5 to 6 kPa i.e. 500 to 600 kg m⁻²) is simply added to the
208 weight of over burden layers (Guily, 1991; Olefs and Lehning, 2010; Howard and

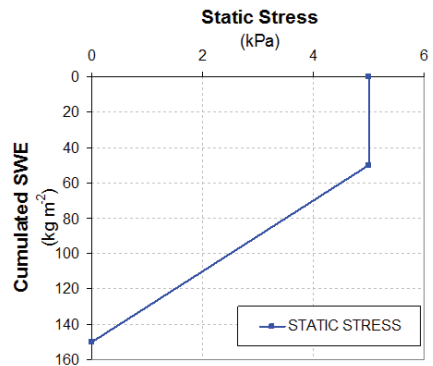


FIGURE 4: The static stress applied on snow layers in Crocus when grooming is carried out

209 Stull, 2014). The deeper the snowpack, the more dampened the load (Thumlert,
 210 2013; Pytka, 2010). We consider here the cumulated snow water equivalent instead
 211 of snow depth to assess the stress applied on a layer. Indeed, SWE combines the
 212 density (Thumlert (2013) showed that the snowmobile stress penetration in the
 213 snowpack decreases with snow density) and depth of layers as the product of both.
 214 The resulting static stress (Figure 4) is constant (5 kPa) for the first 50 kg m⁻² of
 215 snow e.g. the first 50 cm of fresh snow (density 100 kg m⁻³) or the first 10 cm of
 216 older snow (density 500 kg m⁻³). The stress then decreases linearly with increasing
 217 SWE until 150 kg m⁻² of snow e.g. 1.5m of fresh snow (density of 100 kg m⁻³) or
 218 30 cm of older snow (density 500 kg m⁻³).

219 2.3.2. *Tiller effect*

220 The tiller is an additional tool mounted at the rear of a grooming machine and
 221 consists of a high speed rotating shaft (cutter bar) with multiple tines (Figure 3).
 222 Its action is basically to increase the density of the snow-by loading the snowpack
 223 with extra pressure-and to break down snow micro structure into rounded grains,
 224 which leads to higher density due to higher compacity (Fauve et al., 2002; Gully,
 225 1991; Keddy et al., 1979). As a result, all impacted layers are mixed together, their
 226 properties are homogenized and some of them are modified. The effect of the tiller
 227 is simulated in Crocus by modifying the following properties of snow layers :

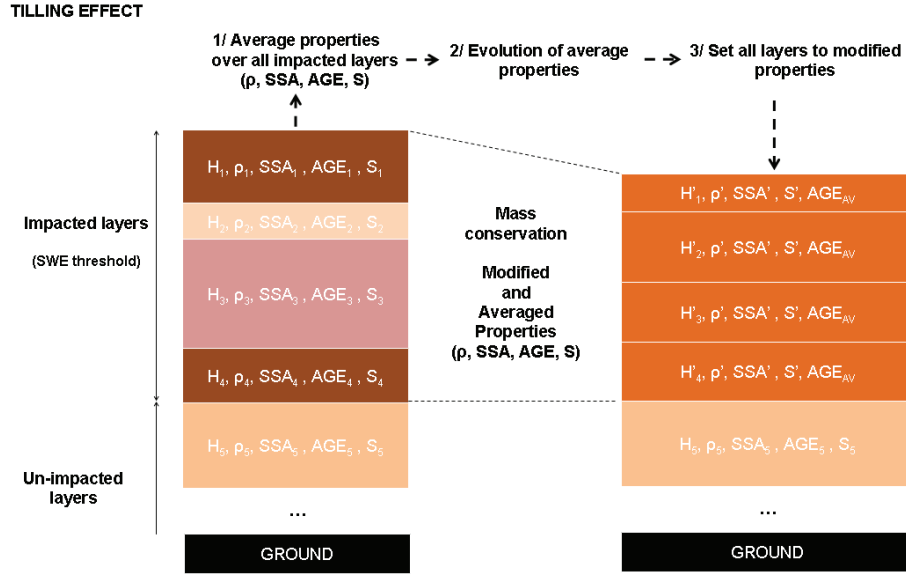


FIGURE 5: The tiller effect as implemented in Crocus

- 228 – Density (ρ)
- 229 – Specific surface area (SSA)
- 230 – Sphericity (S)
- 231 – Age

232 The tiller impacts the top layers of the snowpack within the top 35 kg m^{-2} of
 233 snow (according to the professionals) i.e. the top 35 cm of fresh snow (density 100
 234 kg m^{-3}) or the top 7 cm of older snow (density 500 kg m^{-3}). The sensitivity of
 235 the model to this value is tested in section 2.3.4. After each grooming session the
 236 evolved density ρ'_{layer} of impacted layers is given by :

$$\rho'_{\text{layer}} = \text{MAX}(\rho_{AV}; \frac{2\rho_{AV} + 3\rho_t}{5}) \quad (1)$$

237 Where ρ_{AV} is the weighted average density of impacted layers before grooming,
 238 using the SWE of each contributing layer, and ρ_t (Table 3) is the target value the
 239 density may eventually reach through the grooming process (Fauve et al., 2002).

$$\rho_{AV} = \frac{\sum(\rho_{\text{layer}} * SWE_{\text{layer}})}{\sum SWE_{\text{layer}}} \quad (2)$$

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

$$H'_{\text{layer}} = H_{\text{layer}} * \frac{\rho_{\text{layer}}}{\rho'_{\text{layer}}} \quad (3)$$

247 The sphericity is treated in the same way (Figures 5). The average value of
 248 the age of snow layers is not modified, we simply attribute the average value (cal-
 249 culated similarly to ρ_{AV} , simulating the mixing effect). The SSA of fresh snow is
 250 generally high and decreases with snow metamorphism (Domine et al., 2007), thus
 251 the grooming effect on SSA is

$$SSA'_{\text{layer}} = \text{MIN}(SSA_{AV}; \frac{2SSA_{AV} + 3SSA_t}{5}) \quad (4)$$

252 The evolution of SSA, sphericity and density from equations 1 and 4 through five
 253 successive grooming sessions is shown in Figure 6 from two distinct initial values
 254 (one corresponds to relatively fresh snow while the other is more evolved snow).
 255 Observations from Keddy et al. (1979) or Guily (1991) show that after 5 grooming
 256 sessions, the average density of the snow is 450 kg m^{-3} and that snow microstructure
 257 turns to small rounded grains (0.3 mm). This corresponds to an SSA of $25 \text{ m}^2 \text{ kg}^{-1}$
 258 (Domine et al., 2007) and a sphericity of 90% (Brun et al., 1992). The resulting
 259 standard parameterization of the grooming model is :

- 260 – SWE of penetration (impacted layers) : $\text{SWE}_p = \text{top } 35 \text{ kg m}^{-2}$
- 261 – Target density : $\rho_t = 450 \text{ kg m}^{-3}$
- 262 – Target SSA : $\text{SSA}_t = 25 \text{ m}^2 \text{ kg}^{-1}$
- 263 – Target sphericity : $S_t = 90\%$

264 2.3.3. Grooming schedule

265 Figure 7 describes the decision scheme : whether or not to groom. Grooming is
 266 applied in Crocus if the following criteria are true :

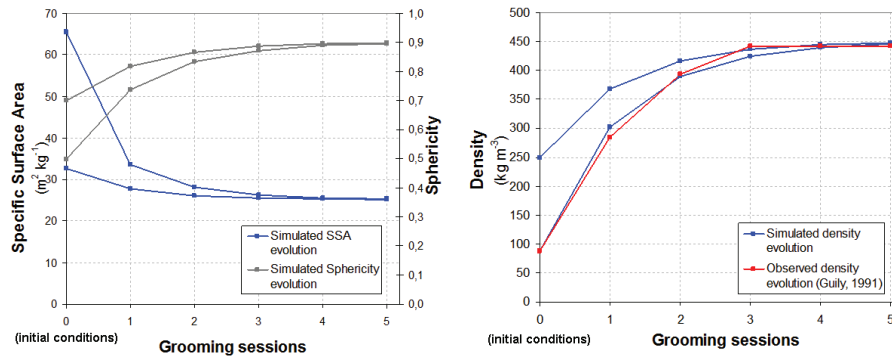


FIGURE 6: The evolution in Crocus of the specific surface area (SSA), sphericity (S) and density (ρ) of impacted snow layers by the tiller after successive grooming sessions from different initial conditions. Once the target value is reached, the tiller still averages the impacted layers properties but 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).

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

273 2.3.4. Sensitivity test of the grooming model

274 Seven configurations of the model parameterization are tested, combining three

275 different levels of every parameter governing the penetration depth of the tiller

276 (SWE_p) and the impact on each snow layer (target values S_t , SSA_t and ρ_t). Table

277 3 contains the standard value (0) and the higher (1) and lower (-1) impact values

278 on snow properties, for each parameter. All parameters are set to the standard

279 value (0) while the (1) and (-1) levels are sequentially attributed to each of them

280 (Table 4). Levels (-1) and (1) of SSA_t and S_t are attributed at the same time

281 to the configurations G5 and G6 since SSA and sphericity can not be viewed as

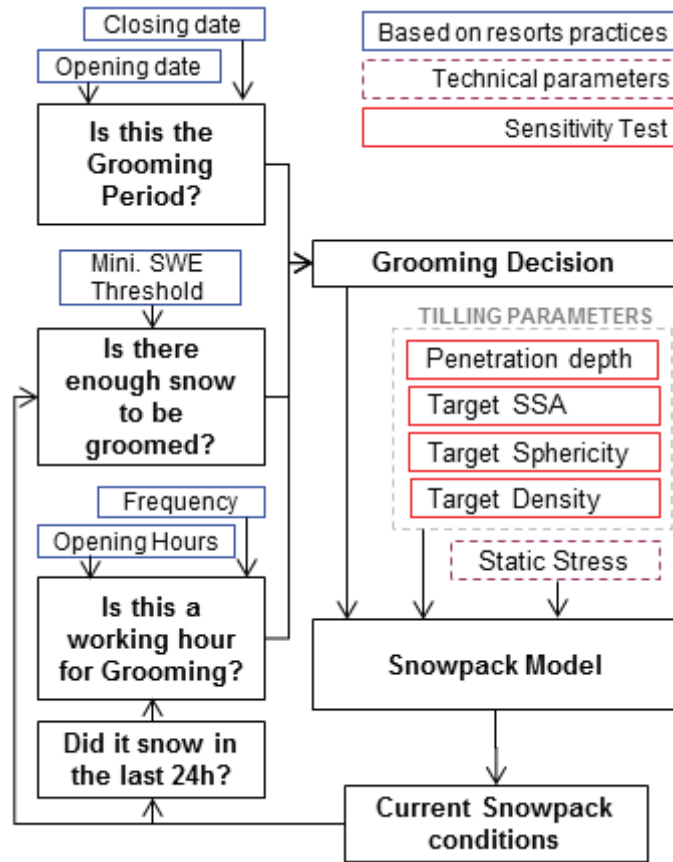


FIGURE 7: Grooming approach implemented in Crocus : decision scheme and main parameters

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 ($^{\circ}C$)
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 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 2.3.2 and 2.4.3). The different combinations of these levels of parameters are specified in Table 4.

Sensitivity test								Sensitivity test							
Grooming configurations								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: 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 3. The configurations G0 and S0 are the standard parameterizations.

282 independent properties

- 283 – G5 : relatively angular snow microstructure with a small grain size ($SSA_t =$
- 284 $35 \text{ m}^2 \text{ kg}^{-1}$ and $S_t = 70\%$)
- 285 – G6 : rather spherical snow microstructure with a larger grain size ($SSA_t = 15$
- 286 $\text{m}^2 \text{ kg}^{-1}$ and $S_t = 100\%$)

287 2.4. Snowmaking approach in the snowpack model

288 Here we describe the snowmaking approach we implemented in the model. In
289 order to focus on the representation of the physical processes in the model, we
290 collected relevant data at the four observation sites (Table 2) and used it as input
291 to produce snow in the model. We collected the season’s total water volume used
292 for snowmaking (TWV) and its monthly distribution at each site (Table 2) which we
293 implemented as the target production in Crocus (Figure 8). For example in Tignes,
294 29 % of the TWV (2317 m^3 , Table 2) was used in November (i.e. 672 m^3) and
295 was spread over 2000 (minimum) to 2800 m^2 (maximum, Table 2), resulting in a
296 target production of 240 kg m^{-2} (simulation with the minimum MM snow) to 336
297 kg m^{-2} (simulation with the maximum MM snow). An efficiency ratio is further
298 applied on these amounts (Section 2.4.4).

299 2.4.1. Production decisions

300 Beyond the quantity of MM snow, the production decision is further dictated
301 by simple rules (Figure 8), based on interviews with snowmakers and literature

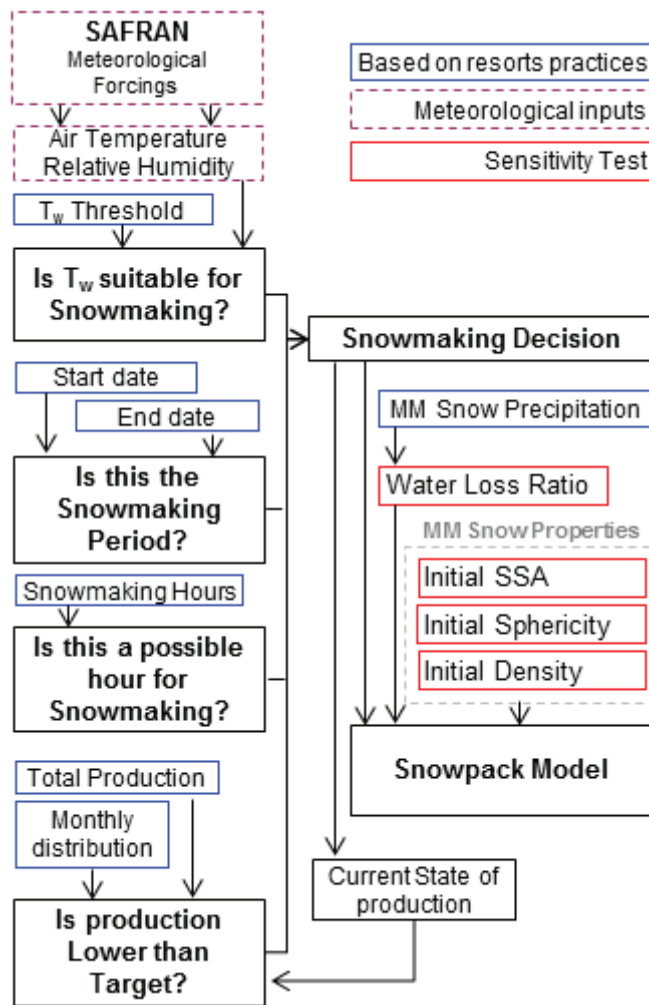


FIGURE 8: Snowmaking approach implemented in Crocus : decision scheme and main parameters (see text for details).

302 (Hanzer et al., 2014; Marke et al., 2014). Production is possible from November
303 1 until March 31. No production is allowed from 08:00 to 19:00 (opening hours).
304 Every evening (19:00) the cumulated snow production is compared with the target.
305 If current production is deficient then production is possible until the next morning,
306 mimicking field practices where snowmaking facilities are generally run for the entire
307 night rather than turned on for only a few hours. Wind speed should not exceed 4.2
308 m s^{-1} (15 km h^{-1}) for snow production (commonly admitted threshold). Lastly, a
309 wet-bulb temperature (T_W) threshold is used to dictate whether or not snowmaking
310 is triggered.

311 2.4.2. *Wet-bulb temperature calculation*

312 The wet-bulb temperature is argued to be the most relevant criterion to deter-
313 mine whether or not snowmaking is possible. (Olefs et al., 2010). For convenient
314 calculation in the model, we used the explicit method from Jensen et al. (1990) to
315 compute T_W from the SAFRAN dry air temperature and humidity (Spandre et al.,
316 2014). This explicit method provides consistent values of wet-bulb temperature wi-
317 thin the range of -15 to 0°C for the dry air temperature and from 30 to 100% for
318 the relative humidity : the maximum error compared to Olefs et al. (2010) implicit
319 method is $\pm 0.3^\circ\text{C}$ (Olefs et al., 2010).

320 2.4.3. *Machine made snow initial properties*

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

329 *2.4.4. Snowmaking efficiency and rate*

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

340 *Production rate.* The MM snow precipitation rate (P_{MM} , $\text{kg m}^{-2} \text{s}^{-1}$) was set at
341 a constant value in the model on each site (Figure 8) and was calculated as the
342 multiplication of the season's observed average water flow on the site (Q_{MM} in kg
343 s^{-1} , Table 2) and the water loss ratio R , divided by the spreading surface of the
344 site (S_{mid} in m^2 , Table 2).

$$P_{MM}(\text{site}) = \frac{Q_{MM}(\text{site}) * R}{S_{mid}(\text{site})} \quad (5)$$

345 *2.4.5. Snowmaking model sensitivity test*

346 Seven configurations (Table 3 and 4) were used to test the sensitivity of the
347 snowmaking model to the parameterization for the MM snow density (ρ_{MM}), spe-
348 cific surface area (SSA_{MM}) and sphericity (S_{MM}) and the wet-bulb temperature
349 threshold which triggers snowmaking (T_W). A sensitivity test of the efficiency co-
350 efficient R (ranging from $R = 100\%$ to 25%) was performed separately, using the
351 standard configuration of the grooming and snowmaking model. All simulations with
352 snowmaking use the standard parameterization of the grooming model (G0, Table
353 3 and 4).

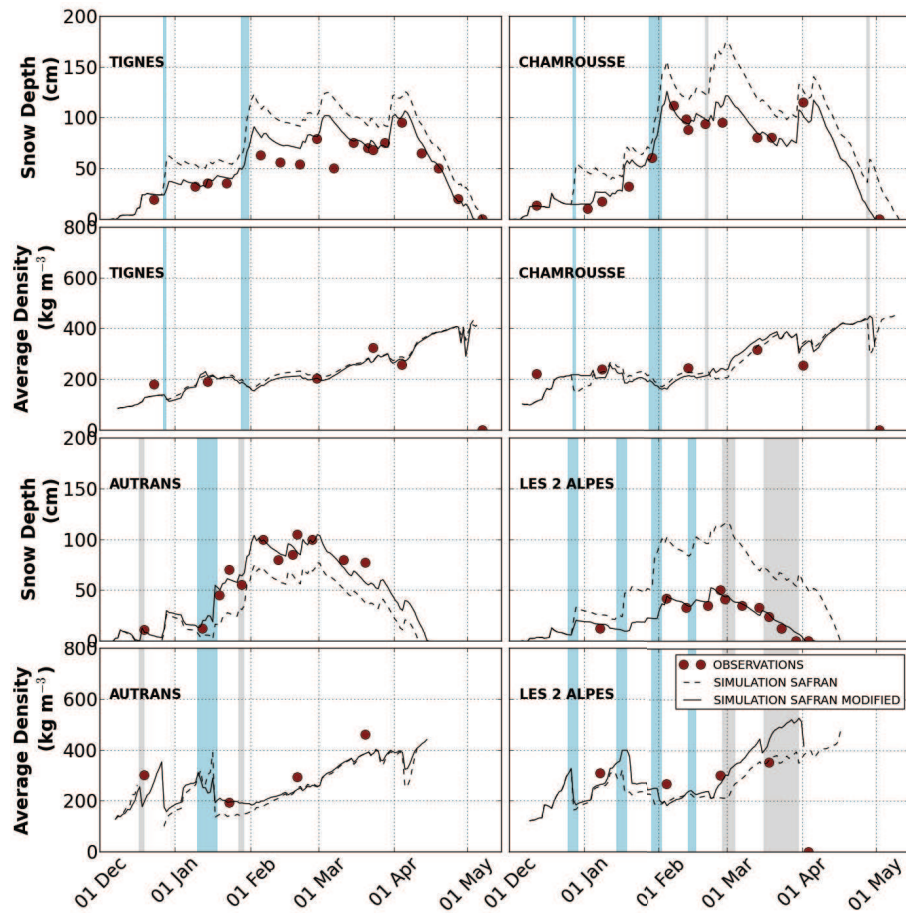


FIGURE 9: Natural snow depth and snowpack average density with respect to in-situ observations (Natural snow site). Runs using SAFRAN forcing data and modified SAFRAN forcing data are shown (Section 2.2.2). The colour blue shows events when the precipitation amount was modified (due to wind drift or 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 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.

354 3. Natural Snow : observations and simulation results

355 *Observations.* By December 1st, none of the observation sites had natural snow
356 cover yet (due to relatively dry and warm conditions in the early season, Figure 9).
357 Significant snowfall occurred during the Christmas holidays and in January, within
358 short periods of intense precipitation. The wind significantly eroded this natural
359 snow on several occasions.

360 Natural snow conditions simulated by SAFRAN-Crocus are shown in Figure 9
361 along with in-situ observations (snow depth and average density). SAFRAN forcing
362 data and modified SAFRAN forcing data (Section 2.2.2) were used. Table 5 contains
363 the calculated Root Mean Square Deviation (RMSD) of these two runs with respect
364 to the mean of the observations. The modified forcing data improves SAFRAN-
365 Crocus accuracy, particularly when the snowpack is very thin (e.g. in Les 2 Alpes).
366 SAFRAN-Crocus provides realistic results for the snow depth (SD), snow water
367 equivalent (SWE) and average density with errors similar to Essery et al. (2013) :
368 about 30 kg m⁻² for SWE and 10 cm for SD. Simulations investigating grooming
369 or snowmaking effects on the snowpack were systematically forced by the modified
370 SAFRAN meteorological data.

371 4. Grooming : observations and simulation results

372 No observation sites with groomed ski slopes only (sites G) were opened to
373 skiers during the Christmas holidays. Groomed snowpack conditions simulated by
374 Crocus are shown in Figure 10 along with in-situ observations (snow depth and

375 average density). All seven configurations of the sensitivity test (Table 3 and 4) are
376 shown as well as the simulation using the static load alone (no tilling effect) and
377 the natural snow simulation. The grooming model yields more realistic simulations
378 of the average density of the groomed slopes than the natural simulation (Table 6).
379 The grooming model is also closer to observations than the static load simulation.
380 Grooming significantly enhanced the snowpack density (Figure 10) and made the
381 average density steadier than in natural snow conditions, ranging between 400 to
382 500 kg m^{-3} . However, regarding the deviation of all grooming configurations and
383 the uncertainty of the observations, it is impossible to conclude which configuration
384 provides better results.

385 The simulated profile of the top 30 cm of the snowpack (Site SM) from January
386 2015 until the end of the observation campaign is shown in Figure 11. On these
387 dates and within the top 30 cm, we assume that there is no MM snow which is
388 located more deeply in the snowpack from early January (section 5). The impact of
389 grooming on natural snow can be observed with all seven simulation profiles : (Table
390 3 and 4), the static load alone, the natural simulation and the observations. The
391 greater homogeneity of groomed layers with respect to natural snow layers appears
392 very clearly for both SSA and density profiles. The density values calculated by the
393 grooming model are very consistent with observations.

394 The model is proven to provide realistic simulations of groomed snowpack condi-
395 tions and we believe it could now be used to investigate the snowpack internal
396 physical processes which occur when grooming natural snow.

397 **5. Snowmaking : observations, simulations and discussions**

398 *5.1. Evaluation of wet-bulb temperature (T_W) calculation*

399 *Observations and simulations.* The wet-bulb temperature calculated with the dry
400 air temperature and relative humidity from SAFRAN was compared with local mea-
401 surements by snow gun sensors (Figure 12). We limited the period (December 1st to
402 February 17th) to the longest time for which sensor data were available in all three
403 resorts (Autrans could not provide these data for technical reasons). A detailed ana-

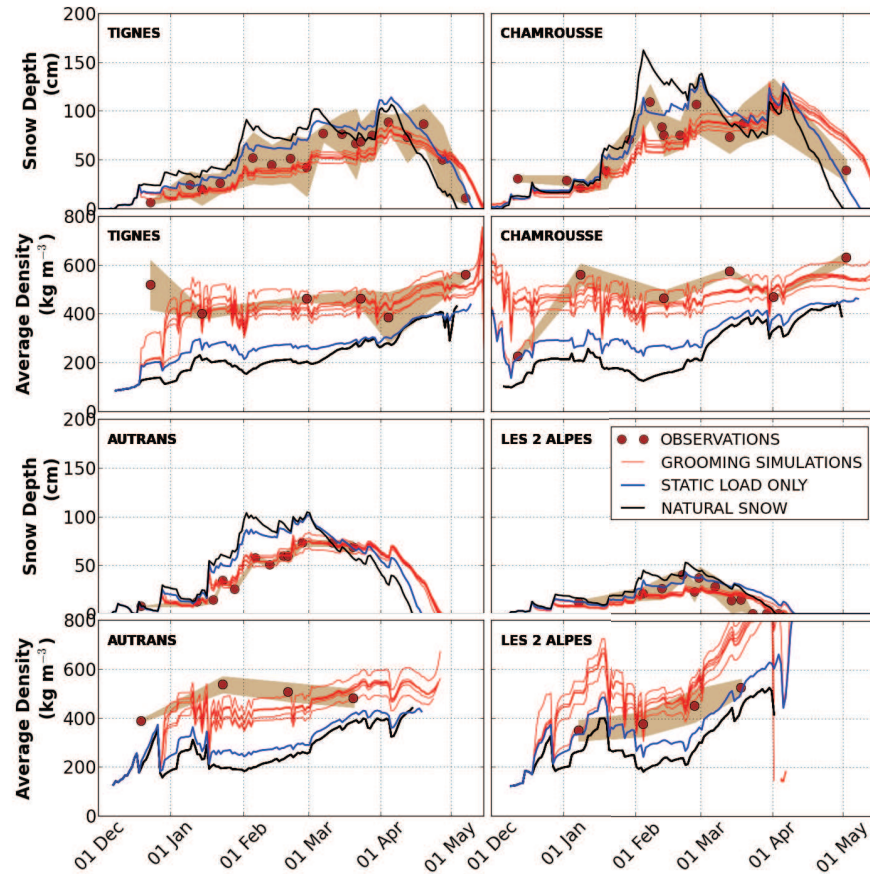


FIGURE 10: Grooming impact on snowpack properties (snow depth, average density). All seven configurations of the sensitivity test (Table 3 and 4) are shown as well as the simulation using the static load alone (no tilling effect) and the natural snow simulation. The brown envelope corresponds to \pm the standard deviation of observations around the average value.

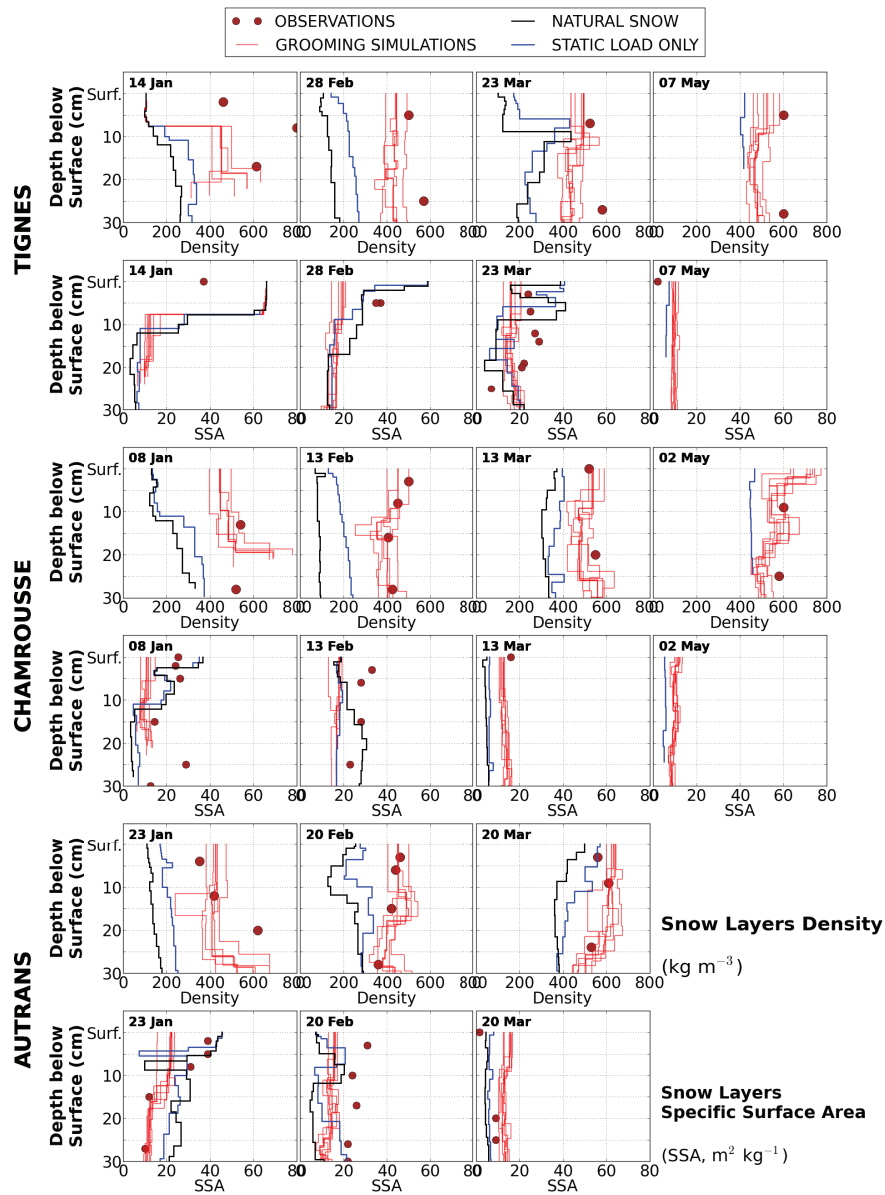


FIGURE 11: Impact of grooming on SSA and density profiles within the top 30 cm of the snowpack. All seven configurations of the sensitivity test (Table 3 and 4) are shown as well as the simulation using the static load alone (no tilling effect) and the natural snow simulation. The natural snow curve does not appear in May since there is no snow on these dates.

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 6: RMSD of simulated groomed snowpack conditions (Grooming standard configuration G0, see section 2.3.2, Table 3 and 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.'

404 lysis of T_W during this period showed that the measured T_W by snow gun sensors
405 was 1 to 2 °C warmer than T_W calculated from SAFRAN data (data not shown,
406 consistent with Figure 12). The cumulated time for low wet-bulb temperatures (<
407 -6°C) was higher with T_W calculated from SAFRAN data. The cumulated time for
408 T_W below -10°C was very low when based on measured T_W .

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

418 5.2. Snowmaking impact on snowpack properties

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

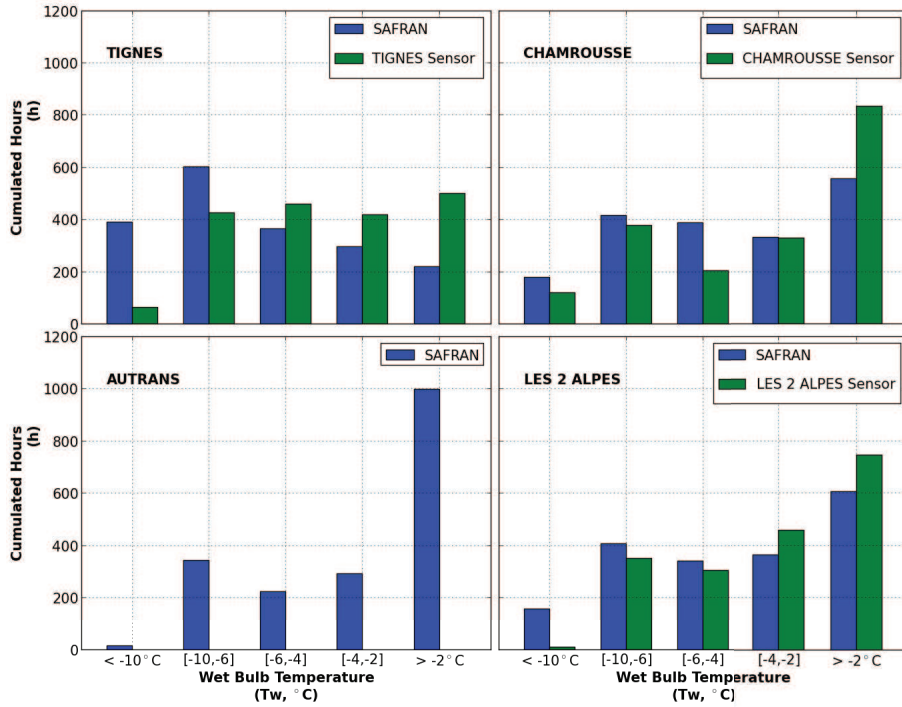


FIGURE 12: Cumulated hours when wet-bulb temperature falls between specified thresholds from December 1st to February 17th. This was the longest period for which sensor data were available in all three resorts together : Tignes, Chamrousse and Les 2 Alpes. Sensor data were not available for Autrans. Calculations from SAFRAN data and the formulation by Jensen et al. (1990) are also shown for each site.

	Simulated Production time (h)	Observed Production time (h)	Simulated Average T_W (°C)	Observed Average water flow (Table 2, $m^3 h^{-1}$)	Average water flow ($m^3 h^{-1}$) 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 7: Simulated production time and average T_W (when production occurred) using the standard configuration of the model (Section 2.4.3, Table 3 and 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.

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 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).

423 *Simulations.* Table 7 shows the simulated production time, the average T_W (when
424 production occurred) using the standard configuration of the model (Section 2.4.3,
425 Table 3 and 4) along with the observed production time and average water flow
426 (also in Table 2). The model may have produced up to one night more than the
427 observations.

428 The wet-bulb temperature (from SAFRAN) and the production history (daily
429 amount of produced snow, in cm, assuming $\rho_{MM} = 600 \text{ kg m}^{-3}$ and $R = 100\%$)
430 using the standard configuration of the snowmaking model (Section 2.4.3, Table 3
431 and 4) are shown in Figure 13. The timing of production is consistent with the target
432 (Table 2). In all resorts a large part of the production occurred for low temperatures :
433 the average T_W of production is below -6°C in every resort (Table 7).

434 The snowmaking model provides a more accurate representation of ski slopes
435 than natural simulations but also significantly improves the results from the groo-
436 ming only simulation both in terms of snow depth and average density (Figure 14
437 and Table 8). The deviation between the seven configurations of the model (Table 3
438 and 4) is low which proves that the model is consistent and reliable when faced with
439 slight changes of the values of parameters. However, regarding the uncertainty of
440 the observations, the question of which configuration provides better results remains
441 inconclusive.

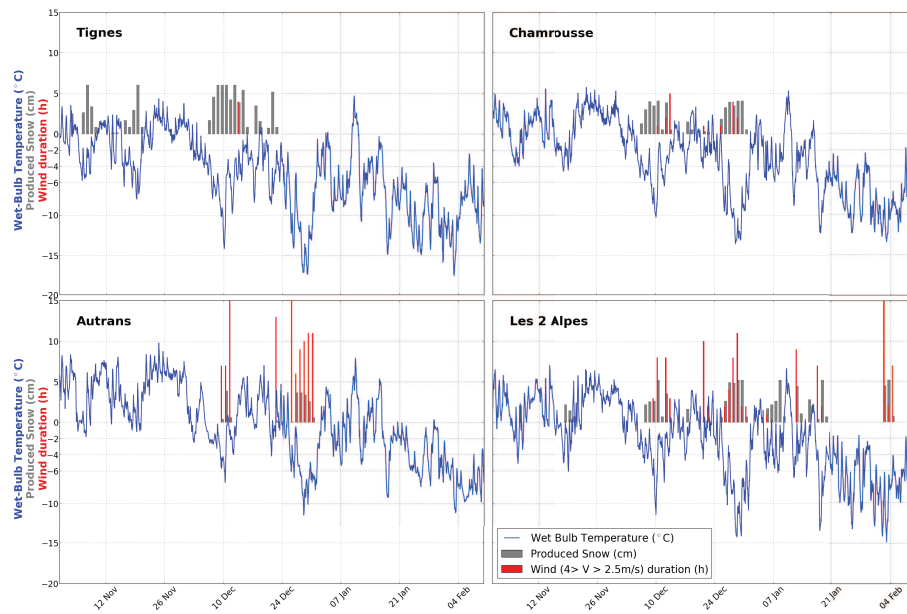


FIGURE 13: Wet-bulb temperature (from SAFRAN) and simulated production history (daily amount of produced snow in cm, assuming $\rho_{MM} = 600 \text{ kg m}^{-3}$ and no water loss i.e. $R = 100\%$) using the standard configuration of the snowmaking model (Table 3 and 4). The wind duration from SAFRAN data (wind speed $4 \leq V < 2.5 \text{ m s}^{-1}$, in hours) is shown for days when production occurred.

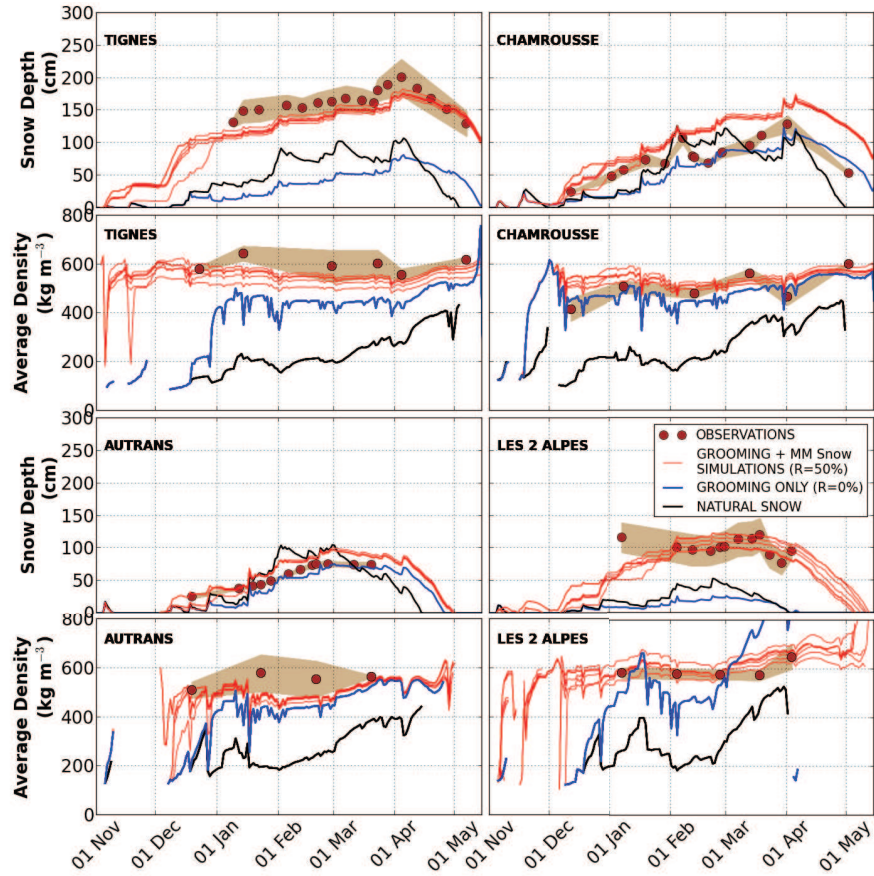


FIGURE 14: Grooming plus snowmaking snowpack conditions simulated by Crocus as well as in-situ observations (snow depth and average density). All seven configurations of the sensitivity test (using a ratio $R = 50\%$, Table 3 and 4) are shown with grooming only (no production) and natural snow properties.

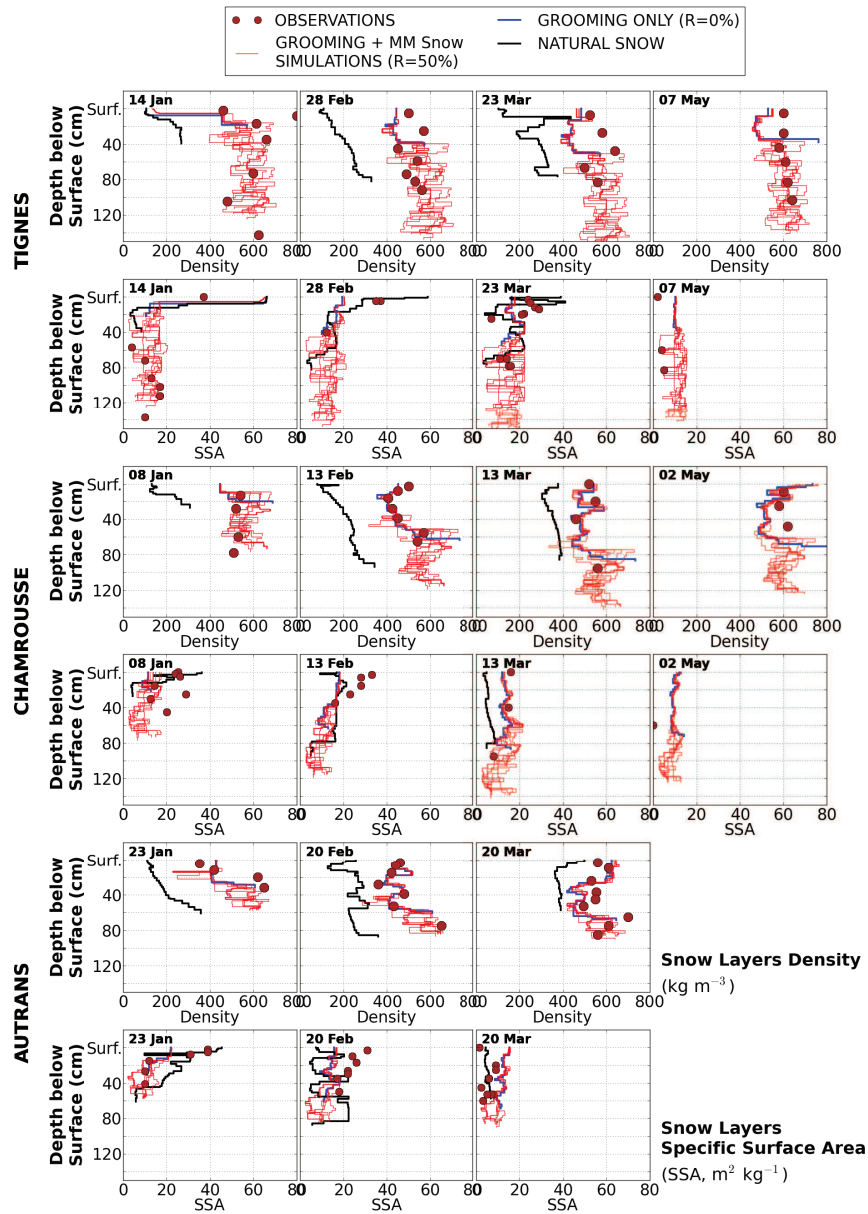


FIGURE 15: Impact of grooming plus MM snow on SSA and density profiles of the top 150 cm of the snowpack simulated by Crocus along with in-situ observations. All seven configurations of the sensitivity test (using a ratio $R = 50\%$, Table 3 and 4) are shown with grooming only (no production) and natural snow profiles. 29

442 The model clearly yields realistic snow layer properties (density and SSA, Figure
443 15). All SSA and density profiles from the seven configurations of the snowmaking
444 model (Table 3 and 4) are shown with grooming only (no production) and natural
445 snow profiles (Figure 15). There is no deviation between simulations within the
446 top 30 cm, as this is groomed natural snow only (section 4). Below this depth,
447 simulation results surround the observations and provide consistent results.

448 *Discussion.* Even if neither described nor evaluated in this paper, snowmaking could
449 be governed in the model by ongoing snowpack conditions (similarly to Hanzer et al.
450 (2014)) and water flow derived from meteorological conditions if needed (Olefs et al.,
451 2010). We set the values for water flow to a constant value in the model, although
452 there is evidence that they may depend on the ongoing meteorological conditions
453 (Olefs et al., 2010; Hanzer et al., 2014). To assess the impact of this assumption
454 in view of the existing knowledge, the average water flow was calculated for each
455 site using an alternative approach. This was done by using the linear equations by
456 Olefs et al. (2010) with respect to the simulated average temperature T_w during
457 production periods (Table 7) and with comparison to the observed constant value
458 we used in the model (Table 2 and Equation 5). The equations by Olefs et al.
459 (2010) provided significantly lower water flow values than the observations in Tignes,
460 Autrans and Les 2 Alpes (air water guns, Table 7). A good agreement was found
461 in Chamrousse (fan gun, Table 7). For example in Tignes, the simulated average
462 temperature T_w from SAFRAN when production occurred was -6.5°C , resulting in
463 an average water flow of $8.6 \text{ m}^3 \text{ h}^{-1}$ (equations by Olefs et al. (2010) for air-water
464 guns) while the observed water flow was $12.2 \text{ m}^3 \text{ h}^{-1}$ (Table 2). Hanzer et al. (2014)
465 calibrated the coefficients of the linear relation by Olefs et al. (2010) between the
466 water flow and the temperature in order to match the official product specifications.
467 However this is specific to one snow gun brand and type and may not be used in
468 other situations. Lastly, the uncertainty related to water flow is not the main issue
469 regarding snowmaking efficiency (Table 8, section 5.3).

470 *5.3. Snowmaking efficiency ratio*

471 *Observations and simulations.* The best agreement (based on RMSD) between ob-
472 servations and simulations (section 2.4.5, Table 8) was found for an efficiency ratio R
473 of 50% to 75% in Tignes, 50% to 25% in Les 2 Alpes, 25% to 50% in Chamrousse
474 and Autrans (Figure 16 and Table 8). Even though we expected from literature
475 (Olefs et al., 2010; Hanzer et al., 2014) that the wind and sublimation would signi-
476 ficantly decrease the amount of water converted into MM snow on the ski slopes,
477 the observed efficiency is lower than expected. Olefs et al. (2010) mentioned a wa-
478 ter loss ranging between 15 and 40 % for air water guns while Eisel et al. (1988)'s
479 assessment ranged from 2 to 13% not accounting for wind effects.

480 *Discussion.* Our results point out that the most uncertain parameter for correctly
481 simulating snow properties on ski slopes is the snowmaking efficiency ratio. In com-
482 parison with it, all other processes and parameters have a limited impact on the
483 model's ability to simulate realistic conditions on ski slopes. Accurate estimations
484 of water loss during snowmaking can not be provided due to the uncertainty of our
485 observations (also dependent on the meteorological conditions of the 2014-2015
486 winter season). However, there is a clear distinction between the situations expe-
487 rienced by all four resorts during the winter of 2014-2015 (Figure 13) in which the
488 wind may have an important role to play by significantly affecting the amount of
489 snow reaching the ground (Pomeroy et al., 1993), particularly if slopes are surround-
490 ed by forests (Pomeroy et al., 1998). The best efficiency ratio is in Tignes where
491 no windy conditions occurred during snow production (Figure 13, there is no vege-
492 tation either). On the contrary the worst ratio is in Autrans where windy conditions
493 occurred for every production day and where all ski slopes are surrounded by forests.
494 To the best of our knowledge, no extensive observation of the efficiency of snow
495 guns has ever been reported and more detailed observations are strongly required
496 to provide further analysis concerning this question.

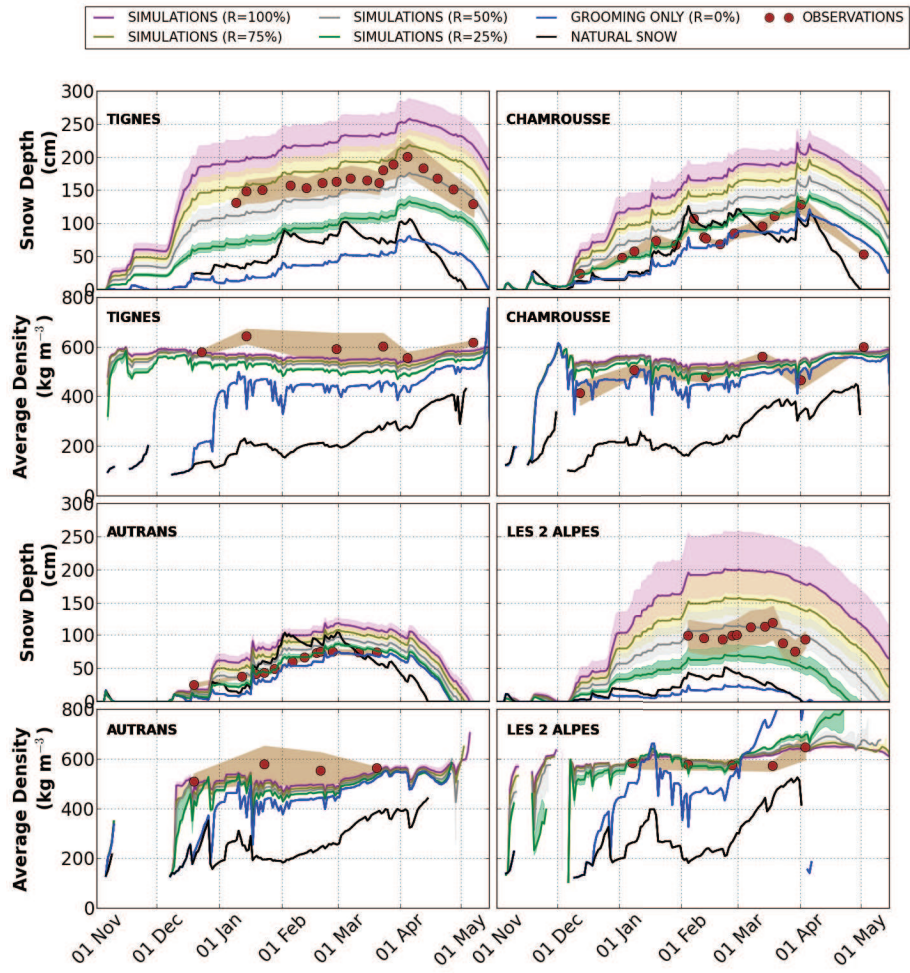


FIGURE 16: Grooming plus snowmaking snowpack conditions simulated by Crocus as well as in-situ observations (snow depth and average density). All four simulations using the standard configurations (and the most likely spreading surface S_{mid}) for the grooming and snowmaking model are shown for ratios from $R = 100\%$ to 25% . Envelopes correspond to the uncertainty of the spreading surface for MM snow using S_{min} and S_{max} (Table 2). Grooming only (no production) and natural snow properties are also shown.

497 6. CONCLUSIONS AND OUTLOOKS

498 Snow management processes (grooming and snowmaking) induce significant
499 change to the physical state and behaviour of the snowpack. Here we described the
500 integration of snow management processes (grooming, snowmaking) into the snow-
501 pack model Crocus. Comprehensive grooming and snowmaking approaches have
502 been implemented in Crocus, based on the literature (Guily, 1991; Fauve et al.,
503 2002; Olefs et al., 2010; Hanzer et al., 2014) and interviews with professionals.
504 Each approach was evaluated with respect to in-situ measurements we carried out
505 during the 2014-2015 winter season in four resorts in the French Alps and the
506 sensitivity to the main parameters was tested.

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

516 The specific properties of MM snow (density, specific surface area, sphericity)
517 are taken into account in the model. The snowmaking model also provided realistic
518 simulations of the snowpack properties with respect to observations. The sensitivity
519 test confirmed that the model is consistent and reliable when faced to changes in
520 parameters. The observed history of production was collected for every observation
521 site and implemented as the production target. Even though the analysis of wet-
522 bulb temperature showed a significant deviation between T_W measured by snow gun
523 sensors and T_W simulated by SAFRAN, it is shown that Crocus is able to produce
524 snow in a realistic manner with respect to the specified rules and current meteo-
525 rological conditions. The snowmaking efficiency however, i.e. the ratio between the
526 mass of machine- made snow on slopes and the water mass used for production

527 was found to be lower than expected when consulting the literature (Olefs et al.,
528 2010) with water loss ranging from 1/3 to 3/4 of the total water mass consumed
529 for snowmaking. The wind and the surrounding vegetation may have a significant
530 impact on the snowmaking efficiency (Pomeroy et al., 1993, 1998).

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

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HIGHLIGHTS

H1. We integrated grooming and snowmaking approaches into the snowpack model Crocus.

H2. The model was tested and proved to be robust to the parameterization.

H3. We realized in-situ observations in four distinct French Alps ski resorts.

H4. The model provides realistic simulations with respect to these observations.

H5. The main uncertainty pertains to the efficiency of the snowmaking process.