INTEGRATING SNOW MANAGEMENT PROCESSES AND PRACTICES INTO A DETAILED SNOW-PACK MODEL. RELEVANCE, APPLICATIONS AND PROSPECTS

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ABSTRACT:

Growing environmental concerns and the ongoing economic crisis push ski resorts operators to pay greater attention to water and energy consumptions and at the same time climate change raises worrying questions about the future of snow industry. Demand for optimization and diagnostics have been growing quickly among professionals and policy makers while paradoxically snow management strategies and impacts on snowpack properties have so far drawn sporadic interest in terms of scientific research. Here we introduce a new numerical tool for snow management analysis and simulation based on the SAFRAN-Crocus model chain. We present the first step of the integration of snow management (snowmaking, grooming) into the detailed snowpack model Crocus. Several ski resorts in the French Alps were interviewed to collect data about machine-made snow production (water volumes, periods of production, snowmaking constraints, etc.) and to assess standard practices (work schedules, priority periods and extra constraints), which we implemented in the model. SAFRAN-Crocus runs provide realistic and consistent results when compared to observations by professionals. Machine-made snow production occurs in the model depending on a predefined production scheme and meteorological constraints (wind, wet-bulb temperature). Machine made snow properties are set to commonly observed properties in terms of density and microstructure characteristics, which differ widely from natural fresh snow properties. Simulation results from *Les 2Alpes* resort (Oisans, French Alps) illustrate the first results. Accounting for machine-made snow production leads to significant enhancement of snowpack conditions for skiing (increased depth and mass) and the season length is extended. The densification due to grooming has also been investigated and shows a significant effect on thermal properties of the snowpack. The season length is also extended thanks to the densification of the snowpack. Overall, the introduction of snow management practices in Crocus appears as a potentially powerful tool to simulate snow conditions on ski resorts tracks. Promising outlooks are presented, among which a diagnostic of resorts ability to face climate change including snow management practices accounting for technical, environmental and regulatory constraints (e.g. water volumes optimization, grooming schedule, etc.).

KEYWORDS: Snow management, grooming, snowmaking, snowpack modeling, French Alps.

1. INTRODUCTION

French resorts sold nearly 58 million tickets in 2013 and winter tourism generated about 10 billion U.S. $. Ski industry is a worldwide market which plays a significant role in the French national economy. As a result, ski fields operators do their best to reach the multiple expectations of both consumers and investors: to ensure opening/closing dates, to guarantee a minimum amount of snow in the early/late season, to maintain safe and homogeneous conditions, etc (DSF, 2013). Operators pay more and more attention to their running costs meanwhile environmental issues (water availability, climate change) are a central concern (Magnier, 2013). For these reasons, heavy demand exists for scientific investigation of both snow management optimization in terms of costs and energy/water consumption and assessments of the ability of snow industry to face climate change (Scott et al., 2007, Damm et al., 2014). Even though snow management probably has an important impact on snowpack properties, most studies on climate change impact do not take it into account and reach conclusions using empirical rules (e.g. the "100-days rule") often solely accounting for natural snow conditions. In addition, simple modeling approaches are generally used to

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compute the time evolution of the snow conditions (e.g. Steiger et al., 2008). In fact, snow management actual effects on snowpack properties are still scarcely understood and detailed snowpack models have not been used to approach this question in a comprehensive manner yet.

Here we introduce new developments targeting the explicit integration of snow management into the detailed snowpack model Crocus. We paid particular attention to be consistent with both physical and socio-economic considerations. Several ski fields operators in the French Alps were interviewed to assess relevant snowmaking periods and operational conditions. In-situ measurements were carried out in ski resorts. Various production practices were identified and integrated into the model to represent the diversity of operators strategies. Similarly, grooming was investigated and a first modeling approach has also been implemented. We here introduce the method we used to assess operator management practices and to integrate them in the model. Results for *Les 2Alpes* ski resort in the French Alps are displayed and discussed. Outlooks are exposed in the last section.

2. MATERIAL AND METHODS

2.1 SAFRAN – Crocus model chain

The multi-layer snowpack model SURFEX/ISBA-Crocus (hereafter, Crocus ; Vionnet et al., 2012) explicitly solves the energy and mass balance of the snowpack in a detailed manner including internal phenomena such as phase change, water percolation, snow compaction, snow metamorphism and their impact on the radiative and thermal properties of the snowpack. The energy budget of the snowpack is explicitly solved at both its interfaces (snow/atmosphere and snow/ground) and the vertical profile of the physical properties of the snowpack is discretized in up to 50 numerical layers ensuring an appropriate description of thermal diffusion through the snowpack.

For applications in French mountain regions, Crocus is usually run using outputs of the meteorological downscaling and surface analysis tool SAFRAN (Durand et al., 1993). The main original feature of SAFRAN is that it operates at the geographical scale of meteorologically homogeneous mountain ranges (referred to as « massifs ») within which meteorological conditions are assumed to depend only on altitude. Based on a robust data assimilation scheme combining large-scale output from numerical weather prediction models, ground-based and radiosonde observations and remotely-sensed cloudiness, SAFRAN provides hourly meteorological conditions in mountain ranges for 300m-spaced altitude bands, which includes not only precipitation (rain and snow rate) and air temperature but also relative humidity, wind speed, incoming longwave and shortwave radiation.

Seasonal snowpack simulations using the SAFRAN – Crocus combination are used in support of daily avalanche hazard forecast. 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).

2.2 Snowmaking approach and assumptions

Thanks to interviews and data collection, we assessed production timing constraints, meteorological conditions and production strategies for several resorts.

The “real world” production strategy is based on water availability, power (electricity) and maintenance costs, specific policy of the resort regarding snowmaking and of course extra need for snow on top of natural snowfalls. Most resorts are now equipped with computer assisted snowmaking installations. The associated softwares record a wide range of parameters (wind, air temperature, water volumes used for snowmaking, water flow, etc. for each snowgun in the resort). Such data were collected for several past winter seasons in several ski resorts in the French Alps, in particular the annual water volumes used for snowmaking as well as the monthly consumption. This has allowed building an average annual volume and distribution and eventually an ideal production curve which could be implemented into Crocus.

Production timing was assessed from interviews with resorts operators. Production is allowed from 1 November until 31 March. No production is allowed from 8am to 7pm (tracks opening hours). Every evening the cumulated volume of water used for snowmaking is compared with the “ideal” production curve introduced above. If current production is deficient then production is potentially allowed until the next morning, mimicking field practices where snowmaking facilities are generally run for the entire night rather than turned on only for a few hours.

Meteorological conditions further dictate whether snowmaking is allowed. Wind speed should not exceed 15 km h^{-1} for snow production (commonly admitted threshold). A wet bulb temperature threshold of -5 °C is used to trigger snowmaking. The wet bulb temperature T_w is argued by all snowguns manufacturers to be the most relevant criteria. It is the temperature, which a moist evaporating surface may approach when its energy balance is zero (Jensen et al., 1990). Olefs et al. (2011) confirmed the interest of wet bulb temperature for snowmaking and described a trial-and-error method to calculate T_w from dry air temperature and relative humidity. This method provided identical results to snowguns manufacturers' abacus. For more convenient calculations, we used the direct method from Jensen et al. (1990) to compute T_w from SAFRAN air temperature and humidity :

$$Tw = \frac{\gamma T + \Delta T_d}{\gamma + \Delta} \qquad (1)$$

where:

T dry air temperature (°C)

T_d dew point temperature (°C)

γ psychrometric Constant (kPa °C^{-1})

$$\gamma = \frac{C_p P}{0.622\lambda} \qquad (2)$$

P atmospheric pressure (kPa)

C_p specific heat of moist air at constant pressure $Cp = 1.013\,\mathrm{kJ\,kg^{-1}\,°C^{-1}}$

λ latent heat of vaporization (kJ g^{-1})

$$\lambda = 2.501 - 2.361.10^{-3} \times T \qquad (3)$$

Δ slope of the saturation vapor pressure curve (kPa °C^{-1})

$$\Delta = \frac{4098 e^{\circ}}{(T_{av} + 237.3)^2} \qquad (4)$$

$$T_{av} = \frac{T_d + T}{2} \qquad (5)$$

e° saturation vapor pressure (kPa) at T_{av} (°C)

$$e^{\circ} = \exp\left(\frac{16.78 T_{av} - 11.69}{T_{av} + 237.3}\right) \qquad (6)$$

More details can be found in Jensen et al. (1990). We compared T_w values with results from the Olefs et al. (2011) trial-and-error method, snowguns manufacturers abacus and Stull et al. (2011) method, and found that the Jensen et al. (1990) provides consistent values of wet-bulb temperature. The wet bulb temperature was calculated with data (temperature, humidity) from SAFRAN and compared with local measurements by snowguns sensors (data from Tignes resort). Wet bult temperature calculated from SAFRAN was consistent with observations.

Last, machine made snow (MMS) is assumed as being very small rounded grains, falling with a density of 350 kg m^{-3}. Microstructure properties of snow in Crocus can be described using the two variables specific surface area (SSA) and sphericity (Carmagnola et al., 2014).

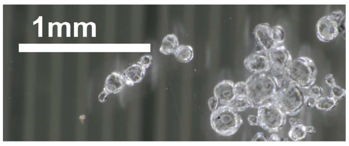

Fig. 1: Macrophotograph of a sample of machine made snow collected during the winter 2013-2014 in Villard de Lans resort (French Alps).

A value of $SSA_{MMS} \approx 22\,\mathrm{m^2\,kg^{-1}}$ is used for freshly produced MMS in Crocus, based on Lafeuille (1988). Sphericity (S) describes the ratio between rounded versus total snow grains (Brun et al., 1992). S=90% is the value used for MMS in Crocus, which accounts for the spherical nature of MMS crystals. When snowmaking happens during a natural snowfall (whose physical properties depend on air temperature and wind speed, Vionnet et al., 2012), the overall properties of newly falling snow is calculated from their specific properties weighted by the incoming mass rates $(\mathrm{kg\,m^{-2}\,s^{-1}})$.

It is generally accepted that the mass yield of snowmaking differs from unity, because of various effects including sublimation, wind erosion, etc. Olefs et al. (2011) estimated a 5 to 40% range of "lost" water. After interviews with different snowmakers we assumed that one third of the water volume is lost on average. So far this loss is assumed to be constant with respect to others factors (altitude and type of snowguns, meteorological factors, etc.). Therefore, the mass flow of snow per unit area ($\mathrm{kg\,m^{-2}s^{-1}}$) in Crocus is equal to:

$$\mathrm{Q_{snow}} = \tfrac{2}{3}\mathrm{Q_{water}} \qquad (6)$$

2.3 Grooming approach

So far the approach in Crocus to model grooming is limited to the densification of snow. Because grooming exceeds densification alone, the term "densification" is preferred to "grooming" in the following.

Our approach to artificial snow densification consists of an extra load applied on the snowpack. The weight of a grooming machine itself is approximately 550 kg m^{-2} (manufacturers online documents, Guily, 1991). Dynamic effects may rise this load to 1000 kg m^{-2} (Pytka, 2010). Extra constraints are applied by additional tools (particularly the tiller). The deeper the snowpack, the more dampened the load. According to Guily (1991), the densification factor due to grooming is constant over the 40 first cm then it decreases linearly until 75cm. Below that depth, it can be neglected.

Following interviews with field grooming specialists, our main approach, alternative to the description of Guily (1991), is to consider the cumulated snow water equivalent SWE_C and not the depth of a snow layer to assess the load applied on that layer. The load is considered constant over the first 50 kg m^{-2} of snow i.e. 50 cm of fresh snow (density of 100 kg m^{-3}) or 10 cm of older snow (density of 500 kg m^{-3}). Then the load decreases linearly with increasing SWE_C until 150 kg m^{-2} of snow i.e. 1.5m deep fresh snow (density of 100 kg m^{-3}) or 30 cm of older snow (density of 500 kg m^{-3}).

The overburden mass σ applied on the snowpack can be summarized as follows, as a function of SWE_C (both in kg m^{-2}):

$$\sigma = 1000 \;\; for \;\; SWE_C \in [0{,}50] \quad (7)$$

$$\sigma = 1500 - 10 \times SWE_C \;\; for \;\; SWE_C \in [50{,}150] \quad (8)$$

$$\sigma = 0 \;\; for \;\; SWE_C \geq 150 \quad (9)$$

Similarly to snowmaking timing frame, we assessed some grooming practices. The grooming is applied in Crocus if the following criterions are true:

- Date is between 1 November and 30 April
- Day is even : tracks are assumed to be groomed one day out of two on average.
- Time is between 6pm and midnight

Exceptions are possible in case of snow falls. If snow falls during day time, grooming is possible from 6pm to midnight even though the day date is uneven. If snow falls during night time, grooming is possible the morning after regardless of the date, from 6am to 9am.

2.4 Test site at Les 2Alpes

Les 2Alpes (L2A) ski resort (Oisans, French Alps) was taken as an example. *Les 2Alpes* ski resort is part of the *Compagnie des Alpes* group, the French largest ski resorts operator. *Les 2Alpes* resort is the twelfth most visited resort in France with over 1.2M tickets sold in 2012/2013 and 37M€ of revenue which is the tenth national rank (Mountain Leader, October 2013). *Les 2Alpes* ski resort is one of the very few French resorts to offer summer skiing on the Mont-de-Lans glacier.

Les 2Alpes resort is equipped with approximately 200 snowguns distributed over the 55 hectares (ha) of strategic tracks (3.6 snowguns per ha to compare with national average of approximately 3 snowguns per ha).

All the reported Crocus runs are based on the specific site "Valentin" track at 2100 m.a.s.l, with western slopes at an angle of 20°. Model runs and data analyses were carried out using data from 2005 to 2014, encompassing a wide range of snow conditions in the ski resort.

3. RESULTS

3.1 Production framework

Over the last 9 winter seasons (2005 to 2014), an average annual volume of 204 000 m^3 of water was used for snowmaking purpose at L2A. Thus, the average mass of water used for snowmaking per unit surface area is 371 kg m^{-2}. Including the loss factor (2/3) the average extra snow mass due to snowmaking is

$$SWE_{snow,SM} = 247\mathrm{kg\,m^{-2}} \qquad (10)$$

The recorded snowguns average water flow is 8m^3/hr. Therefore, the average mass flow per unit area is $\mathrm{Q_{water}} = 8\,10^{-4}\,\mathrm{kg\,m^{-2}\,s^{-1}}$. Regarding the average volume of water used for snowmaking, the average annual time needed for production is $t_{prod} = 128.5hr$. For the 2005-2014 period, the observed monthly distribution of volume of water is given below (with equivalent production duration):

- November 16% (20.5hr)
- December 33% (42.5hr)
- January 28% (36hr)
- February 16% (20.5hr)
- March 7% (9hr)

Total 100% (128.5hr)

From these calculations, we built the ideal production curve for *Les 2Alpes* ski resort (see Figure 2).

Data from three seasons are displayed on Figure 2 in addition to this average curve with the production from Crocus simulations and production duration calculated from actual volumes of water used for snowmaking.

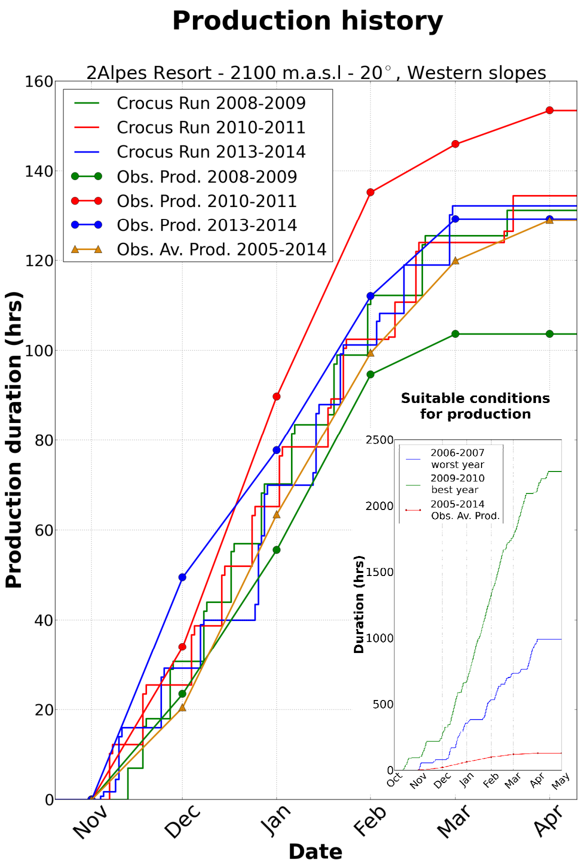

Fig.2: Observed and simulated *Les 2Alpes* ski resort production curve. Obs. Av. Prod. refers to the ideal snow production curve implemented in Crocus.

Figure 2 shows that Crocus actually produces snow in agreement with the specified frame. If the season actual production is close to the average behavior (e.g. 2013-2014), the simulation is very consistent with reality. Scarce (e.g. 2010-2011) or on the contrary abundant natural snow conditions (e.g. 2008-2009) have a deep impact on snowmakers' decisions and are not taken into account yet.

The detail curve displays the duration of suitable conditions for snowmaking (only based on wind and wet-bulb temperature constraints). Even in the worst season, the production availability on that site exceeds by far the needs. Although this may be completely different for another site (different altitudes, etc.), this shows how important it is to take into account extra constraints (costs, water volumes, etc.) to include snowmaking in snowpack modelling.

3.2 Snowmaking impact on snowpack properties

Figure 3 shows the snowpack height and snow water equivalent (SWE) for the winter 2013-2014, as simulated by Crocus. "NATURAL" orange curve shows natural snowpack properties. "Snowmaking Spec. Prop." purple curve shows the snowpack properties including snowmaking with specified MMS microstructure and density.

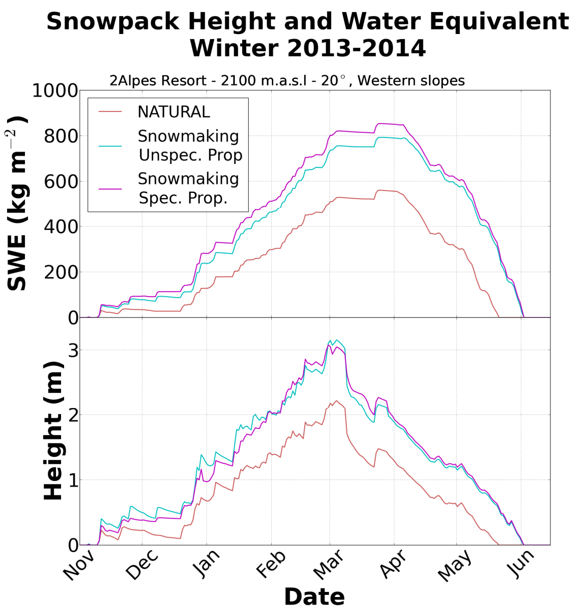

Fig.3: Snowpack height and snow water equivalent, 2013-2014.

By March1st, when the production stopped (Fig. 2), the SWE difference between these two simulations is approximately equal to the produced snow, $SWE_{snow,SM}$. In the early season, a 40 cm thick snowpack existed from mid-November until late December in simulation results including snowmaking while natural snowpack barely reached 30 cm at the maximum. In the late season, the snowmaking curve shows a delay in snow disappearance of approximately two weeks.

The time evolution of the vertical profile of density and SSA of the snowpack that includes snowmaking (purple curve) are displayed in Figure 4.

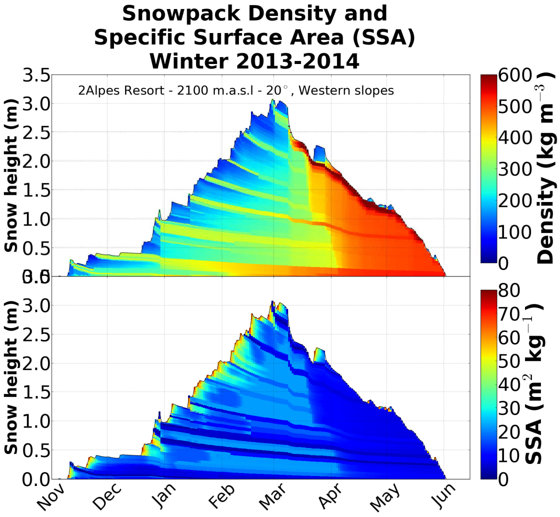

Fig.4: Snow density and SSA for a simulation including snowmaking with assigned snow properties.

The density graph highlights several production sessions when falling snow density is higher than usual (8 sessions at least, with light green color, meaning about 300-350 kg m^{-3}). Similarly on the SSA graph naturally falling snow reaches high SSA values (dendritic snow with SSA>50 m^2 kg^{-1}) while MMS falls with an SSA of approximately 20 to 30 m^2 kg^{-1}.

3.3 *Impact of machine made snow properties on snowpack*

Figure 3 also displays the “Snowmaking Unspec. Prop.” cyan curve which corresponds to a model run that includes snowmaking without assigned MMS properties. These properties (density, shape and size) are treated by Crocus with the same laws as for natural snow falls with respect to meteorological conditions (Brun, 1992).

Snowpack height during snowfalls is higher than without assigning MMS properties since density is much lower than 350 kg m^{-3}. The snowpack SWE becomes lower with time than assigned properties snowpack SWE, up to 50 kg m^{-2}. On the contrary, when spring melt starts, it seems that the forced properties snowpack is more sensitive to spring conditions and snow melt is quicker. Eventually snow disappears roughly at the same date in both cases.

This example shows that assigning specific properties for MMS have an important impact on snowpack behavior. Assigned properties tend to decrease the loss of mass during winter season and to accelerate it during spring melt.

3.4 *Densification impact on snowpack properties*

The densification effect on snowpack properties is displayed on Figure 5. Snow depth is lower after snow falls than for natural snowpack since density is increased. The SWE of densified snowpack appears more resistant against ablation processes than for natural snowpack SWE e.g. during early December melt period.

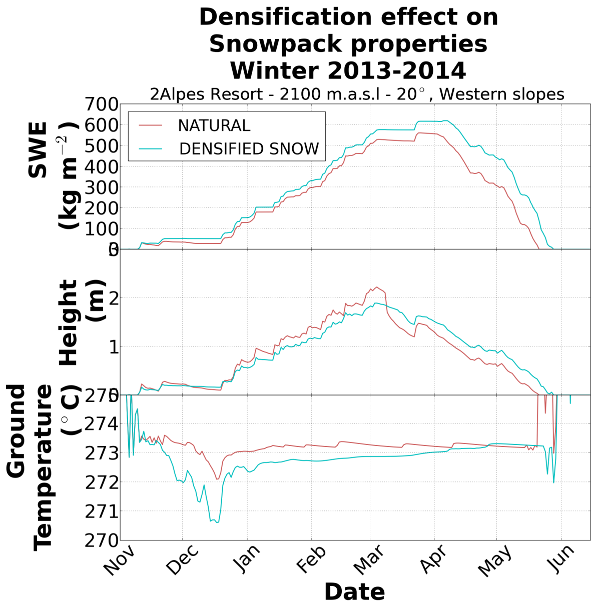

Fig.5: Densification effect on snowpack properties.

Finally when spring melt starts, natural and densified snowpacks behave identically.

4. DISCUSSION

The results displayed in the previous section show that snowmaking and snowpack densification significantly impact snowpack properties and the time evolution of the snowpack state through the winter season. So far measurements of physical properties of snow on ski tracks are virtually inexistent which makes almost impossible to compare our results to measurements. Nevertheless, we consider the snowpack model used to hold sufficient physical basis so that the results of the numerical experiments showed above can already be interpreted as such.

4.1 *Impact of densification*

Density variations drive significant changes to the effective thermal conductivity (Calonne et al., 2011). We believe this is the main reason for the differences between simulations accounting or not for artificial densification. Simulations with artificial densifications are characterized by colder ground, which we attribute to more efficient thermal transfer from the ground to the atmosphere through the snowpack. The snowpack is also generally colder for artificially densified simulations. Detailed analysis of the surface energy budget and internal physical state of the snowpack reveals that the surface energy budget is rather similar between natural and artificially densified snowpacks (data not shown), but more efficient thermal conduction in the densified snowpack leads to more efficient cooling at night, while during the day the warming of the subsurface snowpack by solar radiation absorption proceeds rather similarly (i.e., it depends more on SSA than on density). This leads to a gradual relative cooling of the densified snowpack in comparison with the natural snowpack, which makes it more “resistant” against ablation processes, both at the ground/snow interface, and also due to the presence of cold layers within the snowpack which tend to freeze water percolating from surface melt.

However, note that our simulations consider only densification and not the other impact of snow grooming, which probably also influences surface snow microstructure in addition to density. Our results should thus be considered tentative. Nevertheless, that groomed snowpack tends to melt later than ungroomed snowpack is commonly accepted by resort snow managers. We believe that the densification effect plays a very significant role in explaining this behavior. Nonetheless, our grooming approach is still relatively scarce and deserves to be deeper investigated.

4.2 *Impact of accounting for the physical properties of machine made snow*

As shown above, the impact of assigning or not specific properties to MMS on snowpack state is significant. In a way, freshly-produced machine-made snow layers correspond to strongly evolved natural snow layers and thus both their starting point and future evolution in terms of snow metamorphism is different. The main differences between MM and natural fresh snow are their near-infrared albedo (lower SSA ; Warren and Wiscombe, 1980) and effective thermal conductivity and heat capacity (through higher density ; Calonne et al., 2011).

The impact of a denser snowpack has been addressed in the previous section, and we believe it plays a very significant role in explaining the different behavior of the snowpack accounting for MM snow with and without specific properties at the beginning of the snow season. In terms of snow albedo differences, the effects should maximize in the springtime when the surface energy budget of the snowpack is mostly driven by solar radiation. However, at this period of the year less snowmaking is undertaken so that the differences are less marked.

5. CONCLUSIONS AND OUTLOOKS

The SAFRAN-Crocus model chain was used to investigate snow management impact on snowpack properties. The model provided reasonable results on *Les 2Alpes* resort according to resorts operators, following the integration of snowmaking and grooming (represented tentatively by snow densification) within the detailed snowpack model Crocus. Snowmaking can be simulated in a realistic manner with respect to the average production of previous seasons. The annual variability in water volume used for snowmaking should however be considered. Criterions to adapt the target production should be investigated to improve the ability of the model to match the actual production. Machine made snow microstructure properties are taken into consideration and proved to modify the snowpack behavior facing metamorphism.

Our long term goal remains to build a reliable tool based on Crocus for snow management practices analysis and simulation. We pay a great attention so that this tool respects both physical processes in snowpack and realistic human decisions and strategies. Once this model chain will prove to produce consistent results on actual and current snowpack conditions, we expect to be able to provide relevant information regarding the ability of snow industry resorts to face meteorological variability, and, beyond, climate change challenges.

Further advances in the development and evaluation of the model are needed and planned. Firstly, resorts of different sizes and management strategies will be investigated to assess the diversity in management practices. To achieve that goal, we need the cooperation of resorts' operators to access their data and share their experience. Secondly, a field campaign will be organized during 2014/2015 winter season to gather in-situ observations to compare with simulations carried out using Crocus.

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