SIMULATING SNOW CONDITIONS IN SKI RESORTS WITH THE PHYSICALLY BASED SNOWPACK MODELS AMUNDSEN, CROCUS, AND SNOWPACK/ALPINE3D

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ABSTRACT: Physically based snowpack models are commonly used for the simulation of the snow cover in mountain regions in a high level of detail and process representation. More recently, those models have been adapted to simulate natural and technical snow in ski resorts. Adaptation has been necessary to represent the specific properties of technical snow and snow management practices. This includes the physical description of the snowmaking and grooming processes under consideration of the ski resort infrastructure (snow gun locations and efficiency, water availability, pumping capacity, etc.), but also the associated socioeconomic decisions (when and where to produce snow and to groom). In the frame of the H2020 project PROSNOW, the snowpack models AMUNDSEN, Crocus, and SNOWPACK/Alpine3D will be applied in eight pilot ski resorts across the European Alps for forecasting snow conditions in time scales from days to several months ahead. In our contribution, we present an overview and comparison of these three models including the individual approaches and recent developments for the simulation of natural snow conditions, snowmaking and grooming. We show how individual ski resorts, their infrastructure, and management practices are represented in the models, as well as the approaches for their operational application.

Keywords: snow management, ski resorts, snowpack modeling

1. INTRODUCTION

Most ski resorts in the Alps nowadays are equipped with snowmaking facilities in order to ensure snow reliability during the winter and increase the length of the ski season. While it is increasingly common to employ monitoring techniques such as GPS-equipped grooming devices tracking the snow depth on the slopes, usually information about the future evolution of the snowpack is lacking. Given the appropriate initial conditions and meteorological forecasts, this information can be provided by numerical snowpack models accounting for snow management practices, i. e., the physical descriptions of the snowmaking and grooming processes and the associated socioeconomic decisions. In the past few years much progress has been made in this regard, most notably by the studies by Hanzer et al. (2014) and Spandre et al. (2016, 2017) who integrated snow management into the physically based snowpack models AMUNDSEN (Strasser, 2008) and Crocus (Vionnet et al., 2012). Recently, snow management practices have also been integrated into the SNOWPACK (Bartelt and Lehning, 2002) and Alpine3D (Lehning et al., 2006) models.

These models are currently being applied in the frame of the H2020 PROSNOW project (Morin et al., 2018), where a demonstrator of a meteorological and snow prediction system for time scales ranging between several days and several months ahead is being developed. For eight pilot ski resorts across the Alps, state-of-the-art meteorological and climate forecasts will be used to feed AMUNDSEN, Crocus and SNOWPACK/Alpine3D and deliver information of the future snowpack evolution depending on both the meteorological forecasts and possible snow management strategies.

As the three snowpack models have different backgrounds and original intended purposes (e. g., hydrology vs. avalanche forecasting), they differ in their design and internals (e. g., in terms of onedimensional vs. spatially distributed application, representation of snowpack layering and microstructure, regionalization of meteorological variables). Here, after a short general introduction to the three models, we present an overview and comparison of the current state of integration of snow management and the available parameters allowing to adapt the models to resort-specific management practices. Fi-

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nally, we describe the operational workflow of calculating the snowpack forecasts within PROSNOW in terms of the spatial clustering of ski resorts and the scenarios of management configurations that will be shared by the models.

2. MODELS

In the following, we describe the approaches for integrating snow management in the AMUNDSEN, Crocus, and SNOWPACK/Alpine3D models and the related model parameters. While a more general model description would be out of scope for this paper, an overview of the most important model specifics including a list of references for further information can be found in Table 1.

2.1. Snow production

The production of snow in ski resorts is influenced by several factors, most importantly (i) snow demand (i. e., if there is a need for producing snow at a given location within the resort), (ii) adequate ambient conditions (cold and dry enough air allowing to produce snow, low wind speeds for avoiding blowing snow losses), and (iii) ski resort infrastructure and availability of resources (e. g., number and efficiency of snow guns, water availability, pumping capacity). In the following we describe the general workflow and implementation of snowmaking in the three snowpack models and how these factors are accounted for by discussing the snow production related parameters in the models. These parameters, listed in Table 2, allow to adjust the simulation of snow production according to the infrastructure and snowmaking practices of individual ski resorts. A flowchart of the core snow production procedure as described below is shown in Figure 1. For AMUNDSEN and Crocus, the described functionality is – with the exception of some new developments – mostly identical to the more detailed presentations in Hanzer et al. (2014) and Spandre et al. (2016, 2017).

- Four parameters determine the calculation of (i), snow demand, i. e., when and where in the ski resort snow should be produced: the production period (PP), production time (PT), production threshold (CT), and snow threshold (ST).

  PP defines the period (in the form of a start and end date) in which snowmaking is generally possible. Similarly, PT defines the period (in the form of a start and end time) within each day of PP in which snowmaking is possible. Usually, several subperiods during the season corresponding to different management strategies will need to be considered. Commonly, the season is divided into a base-layer snowmaking period prior to the opening of the resort where snow is produced whenever possible depending on the ambient conditions and a reinforcement snowmaking period afterwards, where snow is produced more selectively depending on demand and only during times when no skiers are on the slopes.

  In addition to the current date and time, the decision if snow should be produced is also influenced by the amount of snow already produced and by the current snow conditions on the slopes. In the models this is accounted for by the production threshold (CT) and the snow threshold (ST) parameters.

  CT allows to specify a certain target water consumption volume which should be met before production is stopped, whereas ST allows to specify that production should be stopped whenever the snow depth on the slopes (i. e., the combination of natural and machine made snow) exceeds a certain value. Again, both of these values can vary depending on PP. Commonly, during the base-layer snowmaking period a certain production threshold is set depending on the available water resources, while during the reinforcement period the snow threshold is used to produce snow only when snow depth on the slopes is below a critical threshold.

- With regard to (ii), ambient conditions, both a wet-bulb temperature threshold (TT) and a wind speed threshold (WT) can be set in order to account for conditions where snowmaking is inefficient (marginal temperatures, too high wind speeds) or not possible at all. If at least one these thresholds is exceeded for a given location, no snow is produced there.

- Finally, if all conditions according to (i) and (ii) are fulfilled, the amount of snow that is actually produced is determined according to (iii), the ski resort infrastructure and available resources.

  The production rate PR ($m^3\,h^{-1}$), i. e., the amount of water that can be converted into snow for a given snow gun and time step, is assumed to be a linear function of the wet-bulb temperature T_w (°C) at the snow gun location:

  $$\mathrm{PR} = a T_w + b \tag{1}$$

  Total snow production volumes for the entire ski resort are calculated differently in the three models. In AMUNDSEN and Alpine3D, being set up as fully spatially distributed models, the number of snow guns per ski slope needs to

Table 1: Overview of the structure and input data of the AMUNDSEN, Crocus, and SNOWPACK/Alpine3D snowpack models. Meteorological variables are: air temperature (T), total/solid/liquid precipitation ($P/P_s/P_r$), relative humidity (RH), shortwave/longwave radiation (R_s/R_l), and wind speed (WS).

	AMUNDSEN	**Crocus**	**SNOWPACK/Alpine3D**
Key reference(s)	Strasser (2008)	Vionnet et al. (2012)	Bartelt and Lehning (2002); Lehning et al. (2006)
Spatial scale	Distributed	Point scale	Point scale (SNOWPACK) / Distributed (Alpine3D)
Vertical snowpack discretization	2–4 bulk layers	Multi-layer	Multi-layer
Temporal resolution	1–3 h	1 h	30 min–24 h
Meteorological input data	T, P, RH, R_s, WS	T, P_s, P_r, RH, R_s, R_l, WS	T, P, RH, R_s, R_l, WS
Meteorological preprocessing	Built-in	SAFRAN (Durand et al., 1993)	MeteoIO (Bavay and Egger, 2014)

be supplied using the NG parameter. Each slope is then divided into segments of equal area according to the number of snow guns. The model snow guns are placed in the center of each segment and produce snow according to the meteorological conditions at these specific locations. In Crocus on the other hand, the snowmaking module is designed to be applied at the point scale: snow production volumes are calculated according to the meteorological conditions at the simulation point and then scaled according to the snow spreading surface parameter (SS), which defines the surface area covered a snow gun.

In AMUNDSEN and Alpine3D, additional snowmaking infrastructure specifics can be incorporated using the water availability (WA), refill rate (RR), and water flow threshold (FT) parameters. WA defines the total water availability for snowmaking at the start of the season, which is then reduced during the season according to the snow guns' water consumption and increased according to RR in each time step. If WA = 0, snow production is stopped. The water flow threshold (FT) parameter on the other hand allows to specify that the total water throughput for the entire resort is limited (as determined by the pumping and piping infrastructure) – if simulated potential production rates exceed this value, production for each snow gun is limited accordingly.

In practice, parts of the water volumes exiting the snow guns according to Equation (1) do not reach the ground of the ski slopes in the form of snow due to both thermodynamic (evaporation and sublimation) and mechanical (wind-driven redistribution) effects. While these water losses can be significant even under ideal conditions (Spandre et al., 2017), simulating them using physical formulations is challenging except for simple estimations of the losses due to thermodynamic effects such as applied in Hanzer et al. (2014). Hence, all three models currently assume a fixed water loss ratio as defined by the WL parameter.

The density of freshly produced technical snow, ρ_{mm}, is modeled as a function of the wet-bulb temperature T_w (°C) in SNOWPACK/Alpine3D:

$$\rho_{\mathrm{mm}} = 1.7261\,T_w^2 + 37.484\,T_w + 605.05. \qquad (2)$$

In AMUNDSEN and Crocus, ρ_{mm} is a fixed parameter value. Similar parameters are implemented in Crocus and SNOWPACK/Alpine3D for the specific surface area ($\mathrm{SSA}_{\mathrm{mm}}$) and sphericity ($S_{\mathrm{mm}}$).

2.2. Grooming

While in practice grooming in ski resorts is performed both in order to redistribute and to compact snow on the slopes, the former is not accounted for by the models, i. e., no explicit transport of snow on the slopes due to grooming takes place. The underlying assumptions are that freshly produced technical snow is immediately distributed evenly over the respective slope surface area, and that the entire snow that is transported downwards due to skiers and wind is later moved back to its original location by the groomers at least daily. The effects of grooming on snow properties (most importantly density) are however explicitly accounted for. Several parameters, listed in Table 3, allow to adjust the schedule and impacts of grooming in the individual models as described below.

Similar to the simulation of snow production, the period and timing of grooming is controlled by the grooming period (GP) and grooming time (GT) parameters, and grooming is only performed where SWE (Crocus) or snow depth (SNOWPACK/Alpine3D) is above a certain threshold (GH).

In Crocus, the densification of the snowpack due to the weight of the groomer is calculated by applying a static stress of 5 kPa to the topmost 50 kg m^{-2}) of snow, then linearly decreasing to 0 kPa at 150 kg m^{-2} of snow. Additional effects due to the tiller mounted to the groomer are applied to the parts of the snowpack specified by the PD parameter (the

Table 2: Adjustable snow production related parameters as implemented in the three models. The last three columns indicate whether the respective parameter is implemented in AMUNDSEN (A), Crocus (C), or SNOWPACK/Alpine3D (S).

Parameter	Symbol	Unit	Function of	Description	A	C	S
Snow demand							
Production period	PP	Date range		Start and end date for snowmaking	×	×	×
Production time	PT	Time range	PP	Daily start and end time for snowmaking during the production period	×	×	×
Production threshold	CT	$kg\,m^{-2}$	PP	Water consumption threshold (SWE equivalent) for stopping production	×	×	–
Snow threshold	ST	cm	PP	Snow depth threshold for stopping production	×	×	×
Ambient conditions							
Temperature threshold	TT	°C	Snow gun type	Wet-bulb temperature threshold for snowmaking	×	×	×
Wind threshold	WT	$m\,s^{-1}$		Wind speed threshold for snowmaking	×	×	×
Ski resort infrastructure and available resources							
Number of snow guns	NG		Slope	Number of snow guns for each ski slope	×	–	×
Snow spreading surface	SS	m^2		Surface area covered by a snow gun	–	×	–
Production rate	PR	$m^3\,h^{-1}$	Snow gun type	Water flow rate for a single snow gun	×	×	×
Water availability	WA	m^3		Total water volume available for snowmaking	×	–	×
Refill rate	RR	$m^3\,h^{-1}$		Water refill rate	×	–	×
Water flow threshold	FT	$m^3\,h^{-1}$		Maximum total water flow	×	–	×
Snow properties							
Water losses	WL			Fraction of water lost due to thermodynamic and mechanical effects	×	×	×
Density	ρ_{mm}	$kg\,m^{-3}$		Density of machine-made snow	×	×	–[1]
SSA	SSA_{mm}	$m^2\,kg^{-1}$		Specific surface area of machine-made snow	–	×	×
Sphericity	S_{mm}	%		Sphericity of machine-made snow	–	×	×

[1] Density is parameterized according to Equation (2)

topmost 35 $kg\,m^{-2}$ by default): densification is parameterized as

$$\rho_{\text{groomed}} = \max\left\{\rho_{\text{av}}, \frac{2\rho_{\text{av}} + 3\rho_t}{5}\right\}, \tag{3}$$

where ρ_{av} is the weighted average density of impacted layers before grooming and ρ_t is the target density that should eventually be reached by grooming (Spandre et al., 2016). Sphericity and SSA are altered analogously using the respective target values S_t and SSA_t.

In SNOWPACK/Alpine3D, densification of the topmost layers of the snowpack as specified by the PD parameter is calculated as

$$\rho_{\text{groomed}} = 12.152(448.78 - \rho)^{0.5} + 0.9963\rho - 35.41. \tag{4}$$

In AMUNDSEN, the bulk snowpack density is altered by adapting the parameters of the snow densification parameterization during grooming hours as described in Hanzer et al. (2014).

3. OPERATIONAL WORKFLOW

3.1. Spatial clustering

As in PROSNOW three different models are applied for a range of ski resorts operationally, it is necessary to agree on a common understanding of the way ski resorts are represented geographically, both for technical reasons and for providing information to the stakeholders in a unified way. While this issue is still part of ongoing discussions at the current stage of the project, one currently proposed approach is that each ski resort is divided into a number of so-called ski resort reference units (SRUs), similar to the hydrological response units (HRUs) commonly used in hydrological modeling.

The delineation of SRUs for a given ski resort is left open to the modeling groups within PROSNOW and stakeholders and can be based on characteristics such as terrain elevation, slope, aspect, the presence or absence of snow guns, or production priorities. The SRUs as such constitute the elementary elements that will be processed by the PROSNOW platform and the basis on which model outputs will be presented to the users, however they are not necessarily equivalent to the smallest model

Table 3: Adjustable grooming related parameters as implemented in the three models. The last three columns indicate whether the respective parameter is implemented in AMUNDSEN (A), Crocus (C), or SNOWPACK/Alpine3D (S).

Parameter	Symbol	Unit	Description	A	C	S
Grooming period	GP	Date range	Start and end date for grooming	×	×	×
Grooming time	GT	Time range	Daily start and end time for grooming	×	×	×
Grooming threshold	GH	$kg\,m^{-2}$ / cm	Minimum SWE (Crocus) or snow depth (SNOWPACK/Alpine3D) required for grooming	–	×	×
Penetration depth	PD	$kg\,m^{-2}$	Part of the snowpack affected by grooming	–	×	×
Target density	ρ_t	$kg\,m^{-3}$	Target density that could be reached by grooming	–	×	×
Target SSA	SSA_t	$m^2\,kg^{-1}$	Target specific surface area that could be reached by grooming	–	×	–
Target sphericity	S_t	%	Target sphericity that could be reached by grooming	–	×	–

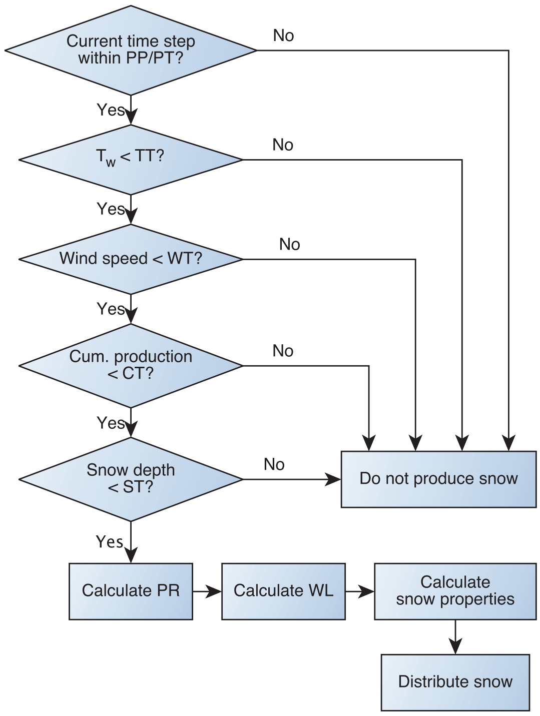

Figure 1: Flowchart of the snow production procedure containing the parameters shared by all three models.

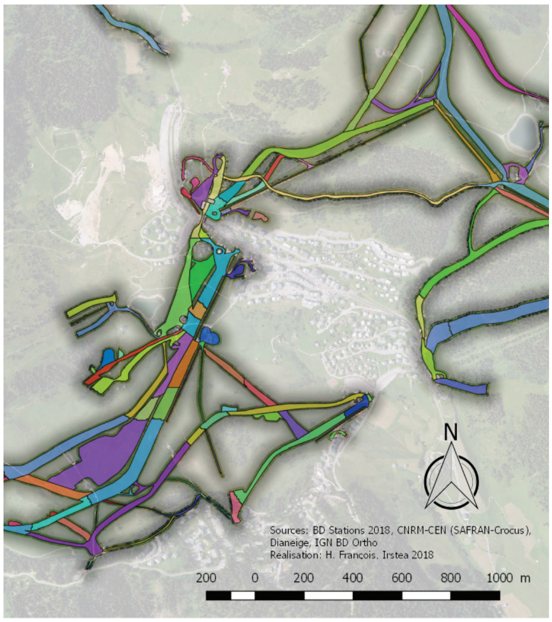

Figure 2: Example of the discretization of a ski resort into SRUs based on the topographic characteristics of the slopes and the presence/absence of snow guns.

units for which the simulations are performed. For example, simulations could still be performed fully spatially distributed on a high resolution grid and only be aggregated to the coarser SRU scale in a post-processing step. This approach will be pursued in the AMUNDSEN and Alpine3D simulations, while the Crocus simulations will directly be performed on the actual SRU scale.

The total number of SRUs for an average ski resort will typically range between several tens and a few hundreds. Figure 2 exemplarily shows a possible discretization of a ski resort into SRUs.

3.2. Model configurations

While the formulation of snow management practices in the models generally allows to adequately simulate real practices (as demonstrated previously by Hanzer et al. (2014) for an Austrian ski resort and Spandre et al. (2016, 2017) for French ski resorts), in practice the parameters listed in Table 2 are not constant but vary both in space and time, as the decision when and where to produce snow is made on a day-by-day basis by the snow production teams in the ski resorts. In order to be able to assist the users in making these decisions, the operational forecasting system developed in PROSNOW will include configurations of different snow management strategies based on the current snow conditions and the meteorological forecasts. Allowing the users to change the model parameters interactively is however not foreseen both due to the computational demands and the increasing complexity of such a system. Rather, a predefined set of configurations which should be representative of the most important management choices will be prepared.

The choice of proposed configurations is listed in

Table 4: Default values (to be adapted for individual ski resorts) for the snow management configurations as used in the operational workflow of PROSNOW. The subscripts b and r indicate the base-layer and reinforcement periods, respectively.

Parameter	Value	Source	Combinations
PP	PP_b = 01 Nov–15 Dec PP_r = 16 Dec–31 Mar	Hanzer et al. (2014); Spandre et al. (2016)	1
PT	PT_b = 00:00–24:00 PT_r = 18:00–08:00	Spandre et al. (2016)	1
PR	1. $PR_{fan} = -4.83 T_w + 3.94$ 2. $PR_{lance} = -3.94 T_w - 4.23$	Hanzer et al. (2014)	2
TT	1. $TT_{fan} = -2\,°C$ $TT_{lance} = -4\,°C$ 2. $TT_{fan} = -4\,°C$ $TT_{lance} = -6\,°C$		2
WT	$WT = 4.2\,m\,s^{-1}$	Spandre et al. (2016)	1
CT	1. $CT_b = 150\,kg\,m^{-2}$ $CT_r = \infty$ 2. $CT_b = 250\,kg\,m^{-2}$ $CT_r = \infty$		2
ST	$ST_b = \infty$ ST_r = 60 cm	Hanzer et al. (2014)	1
IS	1. IS = (0, 0) 2. IS = (1, 0) 3. IS = (0, 1) 4. IS = (1, 0)		4

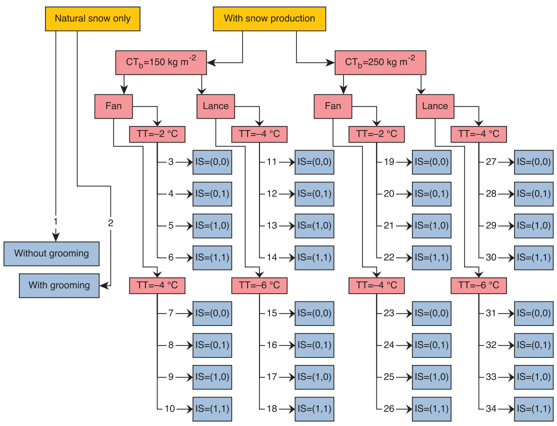

Figure 3: The 34 model configurations as defined in Table 4.

Table 4 and contains a range of *strategic* variables as presented in Table 2 as well as one *tactical* variable, the inhibition switch (IS). The strategic variables concern the snow management choices over the entire season, whereas IS allows to define a set of rules that guide the daily operational choices in the next few days. The selection of configurations listed in Table 4 can be summarized as follows (the individual parameter values, however, can of course be adapted for individual ski resorts):

- The base-layer production period (PP_b) is set to the period from 1 November to 15 December in order for the resorts to be able to open in time for the Christmas holidays. During this period production is possible during the entire day (PT_b = 00:00–24:00). Simulations are performed for two production thresholds (CT_b) after which production should be stopped, namely 150 and 250 kg m^{-2}, respectively (corresponding to snow depths of 30 and 50 cm assuming an average density of 500 kg m^{-3}). No snow threshold (ST_b) is set, i. e., these snow amounts are produced regardless of the natural snow accumulation during this period.

- The reinforcement snowmaking period (PP_r) is set to the period 16 December until 31 March. Here, snow is only produced during nighttime (PT_r = 18:00–08:00) and only if the total snow depth on the slopes is below ST_r = 60 cm.

- Separate simulations are performed assuming the ski resort being equipped with fan guns and lance guns, respectively, using the generic parameterizations described in Hanzer et al. (2014). For each of these snow gun types (corresponding to different production rates for given ambient conditions) again two scenarios are considered when production should be triggered: for fan guns, wet-bulb temperature thresholds (TT) of –2 °C and –4 °C are considered, while for lance guns the thresholds are set to –4 °C and –6 °C.

- An additional variable is introduced which aims at accounting for the short-term management decisions: the inhibition switch (IS) allows to stop snow production on a daily basis within the next two days. IS is defined as a tuple (IS_{d+1}, IS_{d+2}), where a value of 1 for IS_{d+1} or IS_{d+2} indicates that production should be stopped from 18:00 today until 18:00 tomorrow or 18:00 tomorrow until 18:00 on the day after tomorrow. I. e., IS = (0, 0) corresponds to “normal” production according to the settings defined earlier, whereas IS = (1, 1) indicates that all production should be ceased for the next two days.

Combining these settings (two scenarios each for PR, TT, and CT_b, and four scenarios for IS) amounts to 32 separate simulations. In addition, one model run considering untreated natural snow only and one run considering groomed natural snow without snowmaking is included as well, amounting to a total of 34 combinations as shown in Figure 3.

4. RESULTS

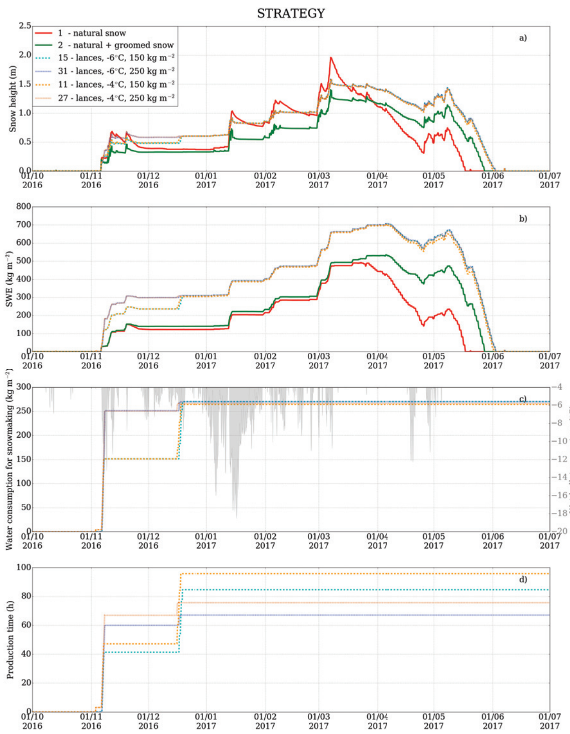

Figure 4: Temporal evolution of snowpack and snow production variables as simulated by Crocus for an SRU at 2100 m a.s.l. in the Les Saisies ski resort and the configurations 1, 2, 15, 31, 11, and 27.

While work on the models and the configuration options is still in progress, Figures 4 to 6 show preliminary results obtained using Crocus, AMUNDSEN, and SNOWPACK/Alpine3D, and demonstrate the influence of the various strategic configurations on the simulated snowpack evolution.

Figure 4 shows the temporal evolution of several variables as simulated by Crocus for an SRU at 2100 m a.s.l. in the Les Saisies ski resort. Results are shown for the configurations 1 (natural snow only), 2 (groomed natural snow), 15 (lance guns, TT = –6 °C, CT_b = 150 kg m^{-2}), 31 (lance guns, TT = –6 °C, CT_b = 250 kg m^{-2}), 11 (lance guns, TT = –4 °C, CT_b = 150 kg m^{-2}), and 27 (lance guns, TT = –4 °C, CT_b = 250 kg m^{-2}).

Figure 5 shows the spatial distribution of SWE as simulated by AMUNDSEN for 16 November 2017

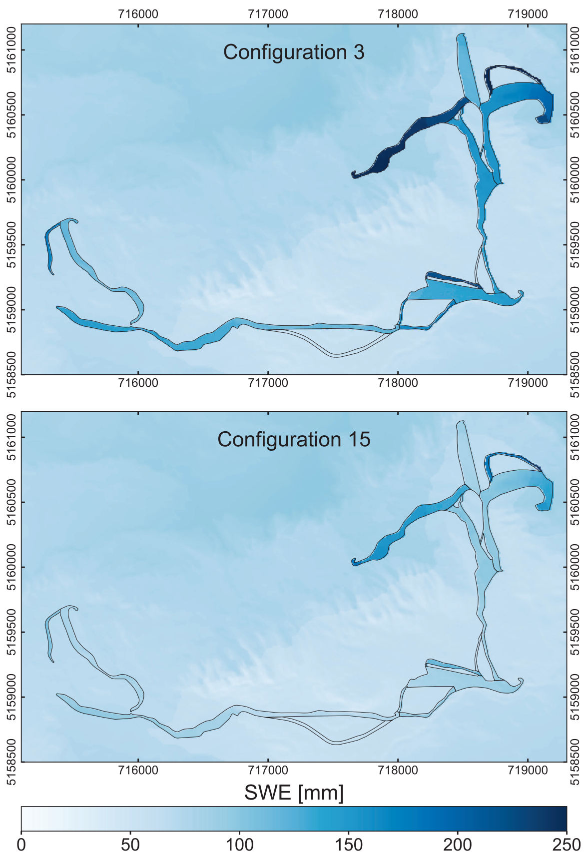

Figure 5: SWE for 16 November 2017 23:00 as simulated with AMUNDSEN (10 m resolution) for the Colfosco ski resort assuming the configurations 3 (top, i. e., fan guns with TT = –2 °C) and 15 (bottom, i. e., lance guns with TT = –6 °C) and start of production on 14 November. Off-slope areas show the simulated natural snowpack.

23:00 in the Colfosco ski resort. Results were obtained by running the model in 10 m resolution without snow production (i. e., configuration 1) until 13 November while switching to configurations 3 (left plot, i. e., fan guns with TT = –2 °C) and 15 (right plot, i. e., lance guns with TT = –6 °C) for the period 14–16 November.

Figure 6 shows the snow depth for a sector in the Lenzerheide ski resort as simulated with SNOWPACK/Alpine3D for 24 December 2011 after starting snow production in early December (left), and for 1 April 2012 assuming no snow production in the last two months (right).

5. CONCLUSIONS AND OUTLOOK

We have presented the current state of integration of snow management practices in the AMUNDSEN, Crocus, and SNOWPACK/Alpine3D models, as well as the approach for the spatial discretization of ski resorts and the selection of management configurations for the operational workflow within the PROSNOW project. First simulation results obtained using these configurations have been presented for se-

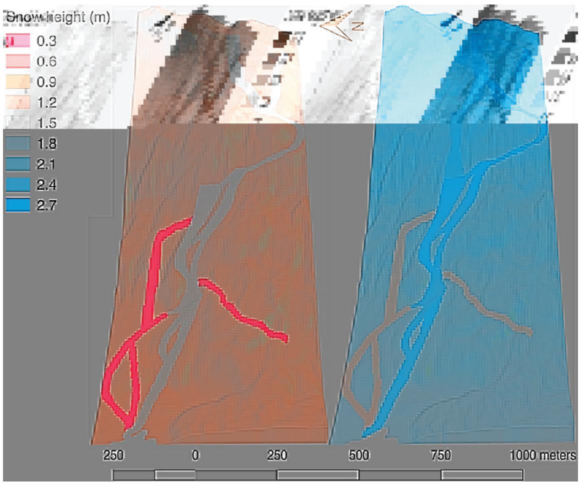

Figure 6: Simulated snow height with SNOWPACK/Alpine3D (5 m resolution) for a sector in the Lenzerheide ski resort assuming different snow height conditions for each slope section. The lowest point is at 1500 m a.s.l. and the highest at 2250 m a.s.l. Left: snow height on 24 December 2011 after starting the machine-made snow production in December. Right: snow height on 1 April 2012 without machine-made snow production for the last two months. Off-slope areas show the simulated natural snowpack.

lected ski resorts. Future work will focus on completing the setup of the models for all PROSNOW pilot ski resorts including the assimilation of local snow production data (i. e., forcing the models with prescribed water consumption volumes) and snow depth measurements. Performance of the models driven by both observed meteorological data and downscaled hindcast data will be evaluated for historical conditions using both in-situ and remotely sensed (satellite-derived snow cover maps) observation data prior to running the models with forecast data. First evaluations of Crocus snowpack simulations (natural snow only) driven by meteorological forecasts in the context of PROSNOW are presented in Carmagnola et al. (2018).

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