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Simulation of snow management in Alpine ski resorts using three different snow models

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ABSTRACT

Snow management, i. e., snowmaking and grooming, is an integral part of modern ski resort management. While the current snow cover distribution on the slopes is often well known thanks to the usage of advanced monitoring techniques, information about its future evolution is usually lacking. Management-enabled numerical snowpack models driven by meteorological forecasts can help to fill this gap.

In the frame of the H2020 project PROSNOW, the snowpack models AMUNDSEN, Crocus, and SNOWPACK/Alpine3D are applied in nine pilot ski resorts across the European Alps for forecasting snow conditions in time scales from days to several months ahead. We present the integration of detailed snowmaking and grooming practices implemented in the three models and show how they can be adapted to individual ski resorts. An ensemble of snow management configurations accounting for a comprehensive set of possible tactical and strategic operational choices is introduced, along with an approach to homogeneously spatialize the results of the three snow models over different areas of the ski resorts. First simulation results are presented for the nine pilot ski resorts in the form of distributed snow water equivalent (SWE) maps along with SWE and snow depth time series for two selected seasons in the past.

1. Introduction

During the past decades, ski resorts throughout the world have become increasingly reliant on snowmaking facilities to complement the natural snow cover. Primarily this is motivated by the desire for on-time planning of ski resort operations and efficient managing of appropriate skiing conditions on the slopes independently of usually highly variable natural snowfall amounts. The goal is to have well controllable snow conditions at the right time, which are smooth and even and robust enough to withstand the impact of today's usual number of skiers (Spandre et al., 2015; Hanzer et al., 2014). As snowmaking operations require considerable investments both in terms of infrastructure and the use of resources (water and energy), ski resorts aim to optimize their snowmaking practices in order to produce snow most efficiently, i. e., in terms of timing, volume, and costs. Often, ski resort managers have to make important decisions under anticipation of future weather and snow conditions. This includes, e. g., identifying the trade-off between producing snow during marginally cold periods vs. waiting for a colder period potentially coming up in the next few weeks (while risking ending up with not enough snow on the slopes), or determining the optimal start date of the base-layer snow production to ensure adequate preparation of the slopes in time for the planned opening date (while risking for a warm spell to melt all of the produced snow again). Although it is increasingly common to employ advanced monitoring techniques such as GPS-equipped grooming devices tracking the snow depth on the slopes, most ski resort managers rely

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solely on short-term weather forecasts for planning snowmaking operations, while information about the future evolution of the snowpack is usually lacking. Given the appropriate initial conditions and meteorological forecasts, this gap can be filled by applying numerical snowpack models accounting for snow management practices, i. e., the physical descriptions of the snowmaking and grooming processes and the associated socioeconomic decisions.

Several simple snow models integrating rule-based snow management have been developed during the past decades (see Steiger and Abegg (2013) for references), mainly in order to assess the impact of climate change on snow reliability and ski tourism activity. In these approaches, the snowmaking strategies are based on general assumptions developed in stakeholder work for selected case study destinations. However, the physical properties of snow were represented in a comparatively coarse manner, and snowmaking (or snowmaking potential) was accounted for using a few simple assumptions. The explanatory power of scenario simulations with these simple models is hence limited to estimates of regional patterns of potential climate change impacts (Abegg et al., 2020). This inspired the development of a new generation of management-enabled snowpack models during the past few years, most notably by the studies by Hanzer et al. (2014) and Spandre et al. (2016b) who integrated snow management into the physically based snowpack models AMUNDSEN (Strasser, 2008) and Crocus (Vionnet et al., 2012), respectively. Recently, snow management practices have also been integrated into the SNOWPACK/Alpine3D model (Bartelt and Lehning, 2002; Lehning et al., 2006). As these three snowpack models have different backgrounds and original purposes (e. g., hydrology vs. avalanche forecasting (Morin et al., 2019)) 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), however they have in common that they are capable of representing the ski resort infrastructure and the specifics of the snowmaking and grooming processes in a considerable level of detail. As it has been demonstrated that they are able to adequately reproduce the real snow conditions on the slopes, they are not only applicable for long-term climate change impact studies (Marke et al., 2015; Spandre et al., 2018) but also for potential real-time applications.

These three 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 nine 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 approaches. Ultimately, these forecasts are intended to help ski resort managers in anticipating important decisions such as inhibiting production under conditions where the produced snow might be subject to melting, or identifying the periods which correspond to the most favorable snowmaking conditions while maintaining reliable snow conditions on the slopes.

In this article, we present the integration of the snow management practices into the three models, along with the first results of the simulations carried over the PROSNOW pilot ski resorts. The goal of this work is twofold. On the one hand, we introduce here an ensemble of snow management configurations accounting for a comprehensive set of possible tactical and strategic operational choices. Those configurations define the common framework used by the different snowpack models to represent consistently the effects of snow management on the snow physical properties, while accounting for the specific practices of individual ski resorts. On the other hand, this work also presents an approach to spatialize the results of the modeling chain over different areas of the ski resorts. With the aim of spatially homogenizing the results across snowpack models, a trade-off between the geometry of the model outputs and the operational needs of the ski resorts has been investigated. Results of snow simulations in terms of snow depth and snow water equivalent (SWE, the mass of snow per surface unit) have been obtained driving the snow models with reanalyzed forcing datasets. A first comparison of the model outputs with natural snow depth values measured by in-situ weather stations is presented.

The paper is structured as follows. 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. Subsequently, we describe the operational workflow of calculating the snowpack forecasts within PROSNOW in terms of the spatial clustering of ski resorts and the management configurations used for the simulations, as well as the setup of the models for the individual ski resorts. Finally, simulation results are presented for all nine pilot ski resorts in the form of time series of snow depth and SWE evolution and distributed SWE maps for two selected seasons of the past and three different snow management configurations.

2. Study sites and data

2.1. Pilot ski resorts

The nine PROSNOW pilot ski resorts that are part of this study are: Seefeld (cross-country part) and Obergurgl in Austria, Colfosco, San Vigilio, and Livigno in Italy, La Plagne and Les Saisies in France, Arosa-Lenzerheide in Switzerland, and Garmisch Classic/Zugspitze in Germany. The choice of these resorts allows representing a large diversity of geographical, climatical and technical characteristics, infrastructure and snowmaking equipment, as well as governance setting and economic dynamics.

Snowpack simulations are performed with AMUNDSEN for the Austrian and South Tyrolean (Colfosco and San Vigilio) resorts, with Crocus for the French resorts, and with SNOWPACK/Alpine3D for the remaining resorts in Switzerland, Germany, and Italy (Arosa-Lenzerheide, Garmisch Classic/Zugspitze, and Livigno). Fig. 1 and Table 1 show the locations and key characteristics of the pilot resorts.

2.2. Model input data

For all three models, required spatial input data for the snow management simulations consists of a digital elevation model (DEM) covering the study sites, the locations of the ski slopes, and the locations and types (at the minimum divided into lances and fans) of the snow guns. Meteorological forcing data for the simulations is based on measurements from automatic weather stations in proximity to the study sites, consisting of at least hourly measurements of air temperature, precipitation, relative humidity, wind speed, and radiation.

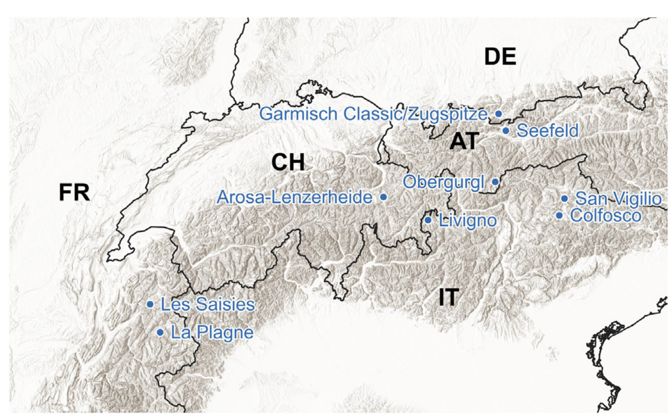

Fig. 1. Locations of the PROSNOW pilot ski resorts.

Table 1
Overview of the nine PROSNOW pilot ski resorts.

Resort	Country	Elevation range (m a.s.l.)	Slope surface area (ha)
Arosa-Lenzerheide	CH	1200–2865	384
Colfosco	IT	1531–2218	64
Garmisch Classic/ Zugspitze	DE	708–2720	66
La Plagne	FR	1250–3250	528
Les Saisies	FR	1150–2069	214
Livigno	IT	1816–2797	448
Obergurgl	AT	1930–2898	107
San Vigilio	IT	1087–2274	119
Seefeld	AT	1179–1251	79

3. Models

All three employed snowpack models, AMUNDSEN, Crocus, and SNOWPACK/Alpine3D, are well-established and have been widely applied in numerous studies throughout the past decades. While an overview of the most important model specifics including a list of references for further information is shown in Table 2, in this article we refrain from a more general model description and focus in the following only on the description of the integration of snow management processes. For details on the model internals, the distribution of meteorological variables, and the calculation of natural snow processes we refer to the respective literature references.

In the following two sections, the functionality and parameters of the snowmaking and grooming modules of the snowpack models are described. For AMUNDSEN and Crocus, the described functionality corresponds for the most part to the more detailed descriptions presented in the respective studies by Hanzer et al. (2014) and Spandre et al. (2016b), however also includes several refinements and adaptations that have since been incorporated. The snow management module of SNOWPACK/Alpine3D has been implemented from scratch through the PROSNOW project and is herein presented for the first time.

3.1. 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 practice, the ski season is commonly 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 often only during times when no skiers are on the slopes (e.g., Spandre et al., 2016a; Steiger and Mayer, 2008). 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 3, 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 Fig. 2.

3.1.1. Snow demand

The calculation of (i), snow demand, i. e., when and where in the ski resort snow should be produced, is determined by the production period (PP) and production time (PT) parameters, which are both specified separately for the base-layer and the reinforcement period (PP_b, PP_r, PT_b, PT_r), as well as the consumption threshold (CT) and snow threshold (ST_b, ST_r) parameters. These parameters are described below in detail.

PP_b and PP_r define the base-layer and reinforcement snowmaking periods (in the form of a start and end date), i. e., the periods where snowmaking is generally possible (which are in practice determined both by legal regulations and by economical and practical considerations such as the planned season opening date). Similarly, PT_b and PT_r define the periods (in the form of a start and end time) within each day of the production period in which snowmaking should be performed (e. g., during the base-layer period snow could be produced all day, whereas during the reinforcement period snow should only be produced during nighttime when no skiers are on the slopes and temperatures are generally lower).

In addition to the date and time, the decision if – and how much – snow should be produced can also be influenced by the amount of snow already produced and by the current snow conditions on the slopes. Common practices are to aim at a certain target snow depth or production volume (depending on the available water resources) during the base-layer period, while during the reinforcement period snow is only produced when snow depth on the slopes is below a critical threshold (e.g., Spandre et al., 2016a; Steiger et al., 2017). In the models this is accounted for by the consumption threshold (CT; kg m^{-2}) and the snow threshold (ST_b, ST_r; m) parameters. CT (implemented in AMUNDSEN and Crocus) allows to specify a certain target water consumption volume which should be met before production is stopped during the base-layer period. The snow threshold parameter (implemented as ST_b for the base-layer period (only available in SNOWPACK/Alpine3D) and as ST_r for the reinforcement period (available in all three models)) on the other hand allows to specify that snow should be produced until the snow depth on the slopes (i. e., the sum of natural and machine made snow) exceeds a certain value.

3.1.2. Ambient conditions

With regard to ambient conditions (ii), both a wet-bulb temperature threshold (TT; °C) and a wind speed threshold (WT; m s^{-1}) can be set in the models in order to account for conditions where snowmaking is inefficient (marginal temperatures, too high wind speeds) or not

Table 2
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); Strasser et al. (2011); Hanzer et al. (2016)	Vionnet et al. (2012); Lafaysse et al. (2017)	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
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
Temporal resolution of input data	1–3 h	1 h	30min–24h
Meteorological preprocessing	Built-in	Often associated with SAFRAN (Durand et al., 1993)	MeteoIO (Bavay and Egger, 2014)

Table 3
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							
Base-layer production period	PP_b	Date range		Start and end date for base-layer snowmaking	×	×	×
Reinforcement production period	PP_r	Date range		Start and end date for reinforcement snowmaking	×	×	×
Base-layer production time	PT_b	Time range		Daily start and end time for snowmaking during the base-layer period	×	×	×
Reinforcement production time	PT_r	Time range		Daily start and end time for snowmaking during the reinforcement period	×	×	×
Consumption threshold	CT	$kg\ m^{-2}$		Water consumption threshold (SWE equivalent) for stopping production during the base-layer period	×	×	–
Base-layer snow threshold	ST_b	m		Snow depth threshold for stopping production during the base-layer period	–	–	×
Reinforcement snow threshold	ST_r	m		Snow depth threshold for stopping production during the reinforcement period	×	×	×
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 parameter 1	PR_a	$m^3h^{-1}\circ C^{-1}$	Snow gun type	First parameter of Eq. (1) to calculate the water flow rate for a single snow gun	×	×	×
Production rate parameter 2	PR_b	m^3h^{-1}	Snow gun type	Second parameter of Eq. (1) to calculate the water flow rate for a single snow gun	×	×	×
Water availability	WA	m^3		Total water volume available for snowmaking	×	–	×
Refill rate	RR	m^3h^{-1}		Water refill rate	×	–	×
Water flow threshold	FT	m^3h^{-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	×	×	–[a]
SSA	SSA_{mm}	m^2kg^{-1}		Specific surface area of machine-made snow	–	×	×
Sphericity	S_{mm}	%		Sphericity of machine-made snow	–	×	×

[a] Density is parameterized according to Eq. (2)

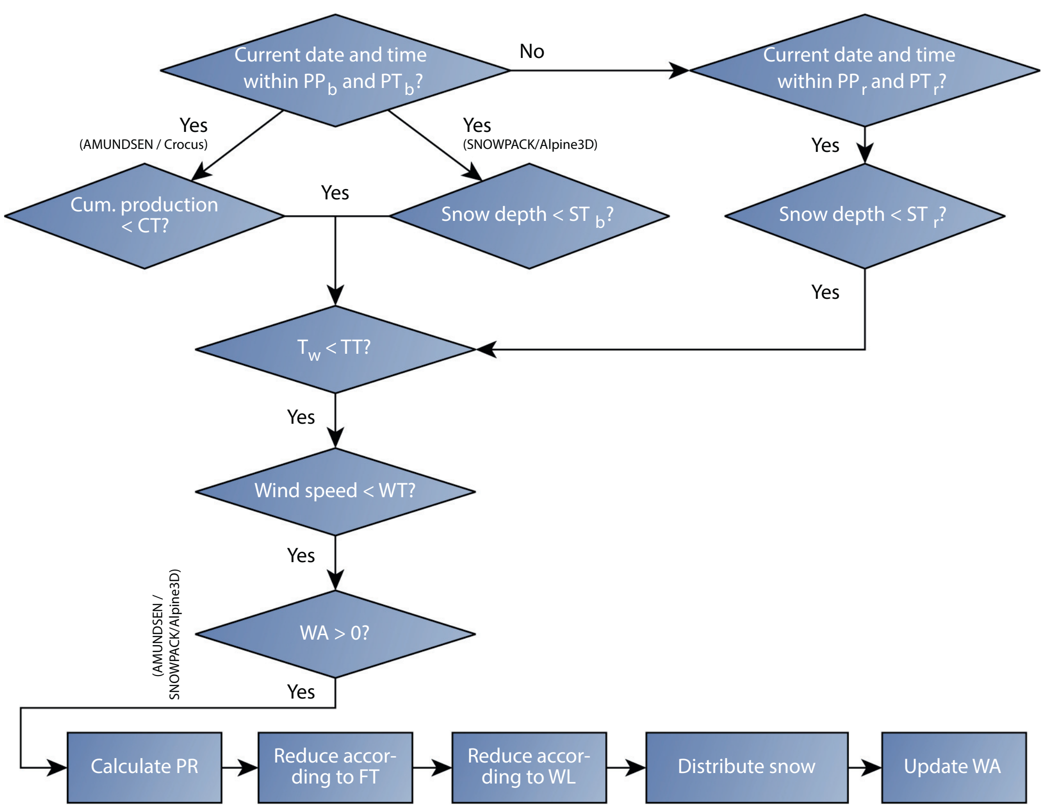

Fig. 2. Flowchart of the snow production procedure in the three models as described in Section 3.1 and Table 3. For all cases not explicitly covered in the chart, no snow is produced.

Table 4
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	$kg\ m^{-2}$ or m	Minimum SWE (AMUNDSEN/Crocus) or snow depth (SNOWPACK/Alpine3D) required for grooming	×	×	×
Penetration depth	PD	$kg\ m^{-2}$ or m	Part of the snowpack affected by grooming (specified as SWE in Crocus and as snow depth in SNOWPACK/Alpine3D)	–	×	×
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	–	×	–

possible at all. If at least one of these thresholds is exceeded for a given location, no snow is produced there.

3.1.3. Ski resort infrastructure and availability of resources

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 parameters PR_a ($m^3\ h^{-1}\ °C^{-1}$) and PR_b ($m^3\ h^{-1}$) are used for calculating 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. PR is assumed to be a linear function of the wet-bulb temperature T_w (°C) at the snow gun location:

$$PR = PR_a T_w + PR_b \tag{1}$$

Total snow production volumes for the entire ski resort are calculated differently in the three models. In AMUNDSEN and SNOWPACK/Alpine3D, being set up as fully spatially distributed models, for each slope (or slope segment) the number of snow guns (NG) to be placed needs to be supplied. 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 by a snow gun (i. e., for a given ski resort, slope, or slope section, this parameter corresponds to the respective surface area divided by the number of snow guns located there).

In AMUNDSEN and SNOWPACK/Alpine3D, additional snowmaking infrastructure specifics can be incorporated using the water availability (WA), refill rate (RR), and water flow threshold (FT) parameters. WA (m^3) 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 ($m^3\ h^{-1}$) in each time step. If all water resources are depleted, snow production is stopped. The water flow threshold (FT; $m^3\ h^{-1}$) 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 Crocus, these parameters are currently not implemented.

3.1.4. Water losses and snow properties

In practice, parts of the water volumes exiting the snow guns according to Eq. (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; Grünewald and Wolfsperger, 2019), 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). Rather, all three models allow to assume a fixed water loss ratio as defined by the WL parameter.

The density of freshly produced technical snow, ρ_{mm} ($kg\ m^{-3}$), is a fixed parameter value in AMUNDSEN and Crocus, whereas in SNOWPACK/Alpine3D it is modeled as a function of the wet-bulb temperature T_w (°C):

$$\rho_{mm} = 1.7261 T_w^2 + 37.484 T_w + 605.05. \tag{2}$$

3.2. 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 in the model simulations 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 densification) are however explicitly accounted for. Several parameters, listed in Table 4, 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. Moreover, as a certain minimum amount of snow is required, grooming is only performed when and where SWE (AMUNDSEN and Crocus) or snow depth (SNOWPACK/Alpine3D) is above a specified 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 topmost 35 $kg\ m^{-2}$ by default): densification is parameterized as

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

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., 2016b). The specific surface area (SSA) and sphericity (S) of snow are altered analogously using the respective target values S_t and SSA_t. Similarly, in AMUNDSEN the bulk snowpack density of snow on the slopes is altered according to Eq. (3). In SNOWPACK/Alpine3D, similarly to Crocus the PD parameter specifies the part of the snowpack affected by grooming, however here referring to a snow depth (0.4 m by default) rather than snow mass. Densification of the affected snowpack layers during a single grooming run is calculated as

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

for $\rho \leq 450\ kg\ m^{-3}$.

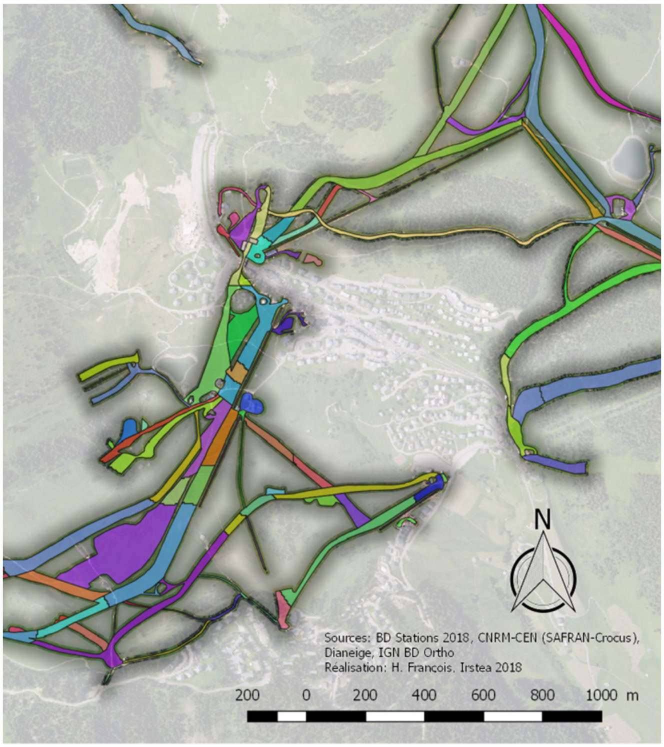

Fig. 3. Example of the discretization of a ski resort (Les Saisies) into SRUs based on the topographic characteristics of the slopes and the presence/absence of snow guns. SRU colors were chosen arbitrarily for visualization purposes.

4. Model setup and workflow

4.1. 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 be used by snow managers in operational forecast mode of the simulations in a homogeneous way. In the jointly developed approach, 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 (e.g., Flügel, 1995).

SRUs are defined by their location and geometry as well as other metadata such as if they are covered by snowmaking facilities or if they are being groomed. The concrete delineation of SRUs for a given ski resort can be based on characteristics such as terrain elevation, slope, aspect, if they are located on a ski slope, the presence or absence of snow guns, or production priorities. It is estimated that the total number of SRUs for an average ski resort will typically range between several tens and a few hundreds. Fig. 3 exemplarily shows a possible discretization of an entire ski resort into SRUs.

While the SRUs constitute the elementary objects that are processed by the PROSNOW platform and the basis on which model outputs are delivered, they are not necessarily equivalent to the smallest model units for which the simulations are performed. Rather, simulations can 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, as illustrated in Fig. 4 using two exemplary SRU discretizations for a ski slope, is pursued in the AMUNDSEN and SNOWPACK/Alpine3D simulations, while the Crocus simulations are directly performed on the actual SRU scale. Similarly, local measurements from the ski resorts that will be assimilated into the snow model simulations for the operational model runs, such as water consumption data or snow depth measurements, will be processed on the SRU scale.

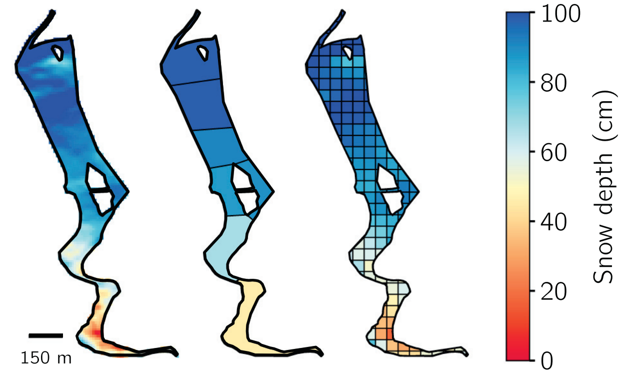

Fig. 4. Aggregation of gridded snow model output data (left, 10 m resolution) for a ski slope to the SRU scale using two exemplary SRU discretizations (center and right).

4.2. Model configurations

While the formulation of snow management processes in the models generally allows to adequately simulate operational practices (as demonstrated previously by Hanzer et al. (2014) for an Austrian ski resort and Spandre et al. (2016b, 2017) for French ski resorts), in practice the parameters listed in Table 3 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 in making these decisions, the operational forecasting system developed in PROSNOW is designed to include configurations of different snow management approaches based on the current snow conditions and the meteorological forecasts. As allowing to change the model parameters interactively would not be feasible both due to the computational demands and the increasing complexity of such a system, a predefined set of configurations which should be representative of the most important management choices will be prepared for each ski resort.

In this work, a single set of parameterizations, according to Table 5,

Table 5
Default parameter values (to be adapted for individual ski resorts) for the snow management configurations as described in Section 4.2. Numbered items are used to indicate different combinations of parameter values. Parameters are according to the definitions in Section 3.1 and Table 3 (IS refers to the inhibition switch as introduced in Section 4.2).

Parameter	Value	Combinations
PP_b	PP_b = 01 Nov–15 Dec	1
PP_r	PP_r = 16 Dec–31 Mar	1
PT_b	PT_b = 00:00–24:00	1
PT_r	PT_r = 18:00–08:00	1
PR_a, PR_b	1. Fan guns: $PR_a = -1.93\ m^3h^{-1} \circ C^{-1}$,	
	$PR_b = 1.58\,m^3h^{-1}$	
	2. Lance guns: $PR_a = -1.58\ m^3h^{-1} \circ C^{-1}$,	2
	$PR_b = -1.69m^3h^{-1}$	
TT	1. $TT_{fan} = -2 \circ C$	
	$TT_{lance} = -4 \circ C$	2
	2. $TT_{fan} = -4 \circ C$	
	$TT_{lance} = -6 \circ C$	
WT	$WT = 4.2\,m\,s^{-1}$	1
CT	1. $CT = 150\,kg\,m^{-2}$	
	2. $CT = 250\,kg\,m^{-2}$	2
ST_r	$ST_r = 0.6\,m$	1
IS	1. IS = (0,0)	
	2. IS = (1,0)	4
	3. IS = (0,1)	
	4. IS = (1,0)	

has been chosen to configure the snowpack models. This makes it easier to present and compare the results of the simulations. In the PROSNOW modeling chain, however, all values of Table 5 will be adapted to match the specific needs of the ski resorts. In practice, each ski resort will have its own set of parameterizations and the possibility to change it every year before the beginning of the winter season. The set of configurations according to Table 5 contains a range of *strategic* variables as presented in Table 3 as well as one additional *tactical* variable, the so-called 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 default set of parameterizations can be summarized as follows:

- 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 consumption thresholds (CT) 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) 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 $ST_r = 0.6$ m (Hanzer et al., 2014).
- 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 -3 and -4 ∘ C are considered, while for lance guns the thresholds are set to -4 and -6 ∘ C. These thresholds are aimed to represent a comparatively aggressive (i. e., producing snow whenever possible even in only marginally cold conditions) and a more conservative snowmaking strategy, respectively.
- The inhibition switch (IS) aims at accounting for the short-term management decisions by allowing 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 (in terms of the current model time step) until 18:00 tomorrow or 18:00 tomorrow until 18:00 on the day after tomorrow. Hence, IS = $(0, 0)$ corresponds to normal, uninterrupted 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, and four scenarios for IS) amounts to 32 separate simulations. In addition, a model run considering untreated natural snow only and a run considering groomed natural snow without snowmaking are included as well, amounting to a total of 34 combinations as shown in Fig. 5.

4.3. Model setup

In this study, we present simulation results for all nine pilot ski resorts demonstrating the functionality of the snow management modules of the three snowpack models and the ability to account for different snow management configurations. The models were first set up for each ski resort for natural snow conditions using standard configurations of the respective snowpack models. The AMUNDSEN and SNOWPACK/Alpine3D simulations were performed in fully distributed mode using a temporal resolution of 1 h and spatial resolutions between 5 and 15 m. The Crocus simulations on the other hand were performed directly on the SRU scale, i. e., by running independent 1-D Crocus simulations for each SRU. SRUs for the two French resorts were derived by dividing the slopes using an automatic approach taking into account their geographic properties (elevation, aspect, and slope) and the presence or absence of snowmaking, resulting in 211 and 374 SRUs for Les Saisies and La Plagne, respectively, with an average area of 1.3 ha.

For AMUNDSEN, gridded hourly meteorological input data was provided by AMUNDSEN's internal meteorological preprocessor using observations from stations surrounding the ski resorts. Interpolated fields from the point measurements are – in the case of temperature, precipitation, humidity, and wind speed – obtained using a combined lapse rate–inverse distance weighting scheme, either using automatically calculated lapse rates for each time step or using prescribed monthly lapse rates. Radiation fluxes are calculated for clear-sky conditions using the parameterizations from Corripio (2002) and corrected using cloudiness fields (Hanzer et al., 2016). Similar approaches were applied for the SNOWPACK/Alpine3D simulations by using the meteorological preprocessing library MeteoIO (Bavay and Egger, 2014). For Crocus, the generation of consistent meteorological input data was carried out by the meteorological downscaling and surface analysis tool SAFRAN (Durand et al., 1993). SAFRAN operates at the geographical scale of meteorologically homogeneous mountain ranges (so-called "massifs"), within which meteorological conditions are assumed to depend only on altitude and aspect. For the analysis of meteorological surface fields, the guess used by SAFRAN consists of vertical atmospheric profiles from numerical models. A robust assimilation scheme corrects the initial guess based on ground-based and radiosonde observations as well as remotely-sensed cloudiness. Thus, SAFRAN provides hourly meteorological conditions for each massif for 300 m-spaced elevation bands.

For setting up the snow management modules, the 34 standard configurations according to Fig. 5 were used. Model parameters not covered by these parameter sets (e. g., the resort-specific infrastructure-related parameters) were adapted to each ski resort using available data provided by the ski resorts where possible, or set to reasonable default values otherwise. It should be remarked that for some resorts water availability (WA parameter) was set to be limited (e. g., to the total reservoir volume), while for other resorts it was assumed to be unlimited either because no exact values were available or because the WA parameter is not implemented in the respective snowpack model (i. e., for the French resorts). However, the limited water availability is already implicitly included in the base-layer production targets (CT and ST_b parameters), hence explicitly setting the WA parameter will in most cases not change the simulated production volumes, since reinforcement production is usually very minor compared to the base-layer production.

Table 6 summarizes the snowpack models, the temporal and spatial resolutions, and the values of the snow management related parameters used for the individual simulations.

5. Results and discussion

In the following, simulation results for each ski resort obtained using the model parameterizations described above are presented. Model runs were performed for two winter seasons representing two comparatively extreme cases in terms of snow characteristics: 2016/17, one of the driest winters in the recent years with many regions in the Alps receiving almost no snow until early January, and 2017/18, an especially snow-rich winter throughout the entire Alps with large snowfalls already in November and December in some regions. For these two seasons, simulations were carried out for all ski resorts using all ten strategic snow management configurations, i. e., (numbers according to Fig. 5) the natural snow-only configurations 1 (no grooming) and 2 (with grooming), and the snowmaking-enabled configurations 3, 7, 11, 15, 19, 23, 27, and 31, i. e., accounting for both fan guns and lance guns as well as different temperature thresholds and base-layer production targets.

The results for each ski resort are presented as follows:

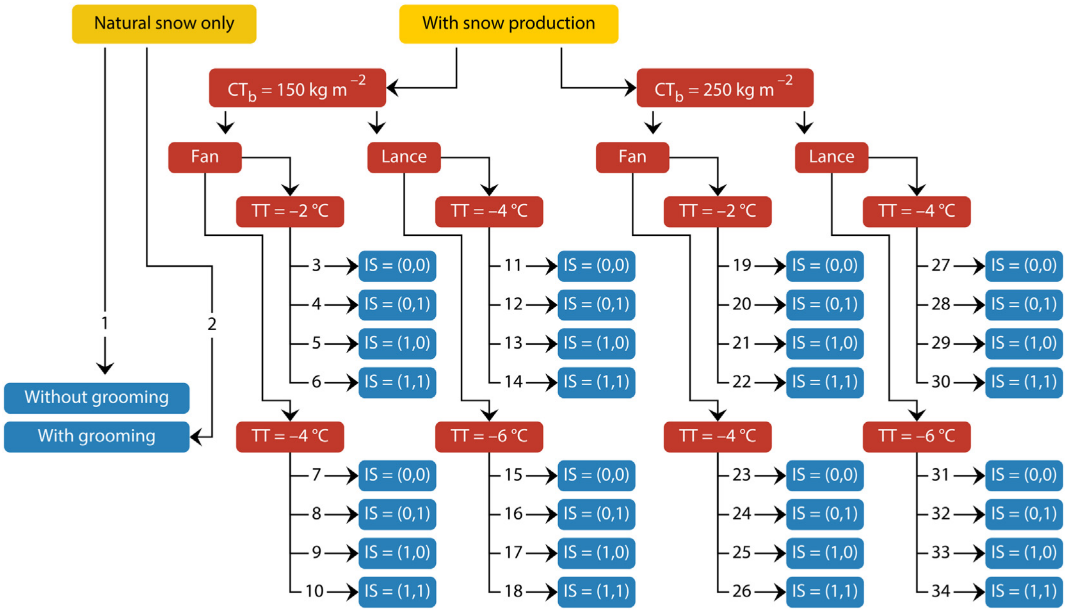

Fig. 5. The 34 model configurations as defined in Table 5.

- Maps showing the simulated SWE distribution for 24 December 2016 and 2017, i. e., at the beginning of the economically crucial Christmas holiday period. The Crocus simulation results for the French resorts are shown for the the defined slope SRUs, whereas the results for the AMUNDSEN and SNOWPACK/Alpine3D simulations are shown for the entire model grids, i. e., including untreated natural snow beside the slopes and without aggregation of the model outputs to the SRU scale.
- Time series of simulated snow depth, SWE, and density for one

Table 6

Snowpack models, temporal and spatial resolution, and values of the snow management related parameters for the simulations presented in this study.

	Colfosco, San Vigilio, Obergurgl	Seefeld	La Plagne, Les Saisies	Arosa-Lenzerheide	Garmisch Classic/ Zugspitze	Livigno
Snowpack model	AMUNDSEN	AMUNDSEN	Crocus	SNOWPACK/ Alpine3D	SNOWPACK/Alpine3D	SNOWPACK/ Alpine3D
Temporal resolution	1 h	1 h	1 h	1 h	1 h	1 h
Spatial resolution	10 m	5 m	SRU scale[a]	10 m	5 m	15 m
Snowmaking parameters						
PP_b	01 Nov–15 Dec	01 Nov–15 Dec	01 Nov–15 Dec	01 Nov–15 Dec	15 Nov–15 Dec	01 Nov–15 Dec
PP_r	16 Dec–31 Mar	16 Dec–31 Mar	16 Dec–31 Mar	16 Dec–31 Mar	16 Dec–01 Mar	16 Dec–31 Mar
PT_b	00:00–24:00	00:00–24:00	00:00–24:00	00:00–24:00	00:00–24:00	00:00–24:00
PT_r	18:00–08:00	18:00–08:00	18:00–08:00	17:00–08:00	17:00–08:00	17:00–08:00
CT (kg m^{-2})	(see Table 5)					
ST_b (m)	(see Table 5)					
ST_r (m)	0.6	0.6	0.6	0.6	0.6	0.6
TT (°C)	(see Table 5)					
WT (m s^{-1})	4.2	4.2	4.2	2.8	2.8	2.8
NG	Slope-dependent	Slope-dependent	n/a	Slope-dependent	Slope-dependent	Slope-dependent
SS (m^2)	n/a	n/a	3300	n/a	n/a	n/a
PR_a (m^3 h^{-1} C^{-1})	(see Table 5)					
PR_b (m^3 h^{-1})	(see Table 5)					
WA (m^3)	Undisclosed[b]	Undisclosed[b]	n/a	Unlimited	Undisclosed[2]	Unlimited
RR (m^3 h^{-1})	0	0	n/a	0	0	0
FT (m^3 h^{-1})	Undisclosed[b]	Undisclosed[b]	n/a	Unlimited	Unlimited	Unlimited
WL	0.3	0.3	0.4	0.2	0.2	0.2
ρ_{mm} (kg m^{-3})	400	400	500	Eq. (2)	Eq. (2)	Eq. (2)
SSA_{mm} (m^2 kg^{-1})	n/a	n/a	23	n/a	n/a	n/a
S_{mm} (%)	n/a	n/a	0.9	1	1	1
Grooming parameters						
GP	01 Nov–30 Apr	01 Nov–30 Apr	01 Nov–30 Apr	01 Nov–30 Apr	15 Nov–31 Mar	01 Nov–30 Apr
GT	21:00–22:00	21:00–22:00	20:00–21:00 (and 06:00–09:00 in case of snowfall)	21:00–22:00	21:00–22:00	21:00–22:00
GH	20 kg m^{-2}	20 kg m^{-2}	20 kg m^{-2}	0.4 m	0.4 m	0.4 m
PD	n/a	n/a	35 kg m^{-2}	0.4 m	0.4 m	0.4 m
ρ_t (kg m^{-3})	450	450	450	450	400	450
SSA_t (m^2 kg^{-1})	n/a	n/a	25	n/a	n/a	n/a
S_t (%)	n/a	n/a	0.9	n/a	n/a	n/a

[a] SRUs were derived using a 30 m DEM. Mean SRU area: 1.3 ha.
[b] Confidential information not to be disclosed.

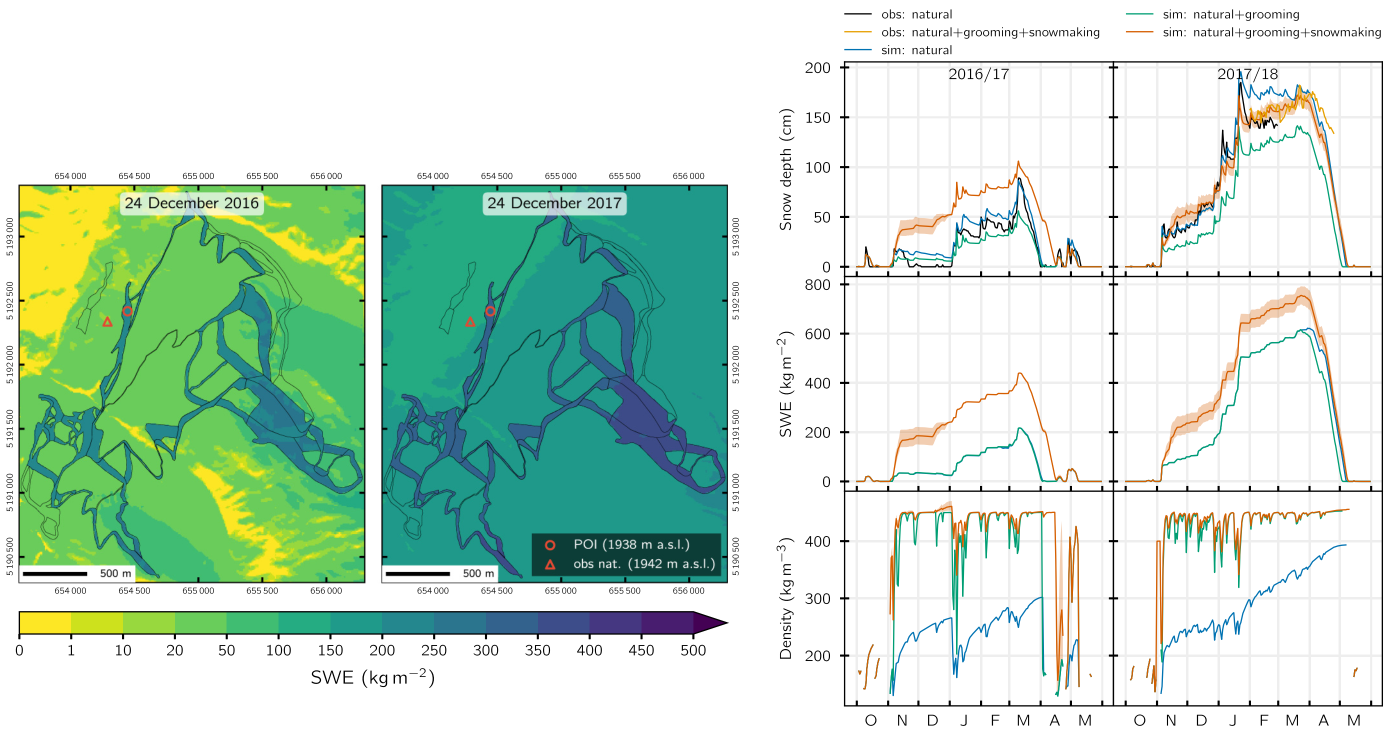

Fig. 6. AMUNDSEN simulation results for the Obergurgl ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1938 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed natural snow depth from a nearby location (indicated with a red triangle in the maps) is shown in black.

selected slope location within the resort based on simulations for the ten configurations. Additionally, both observed natural snow depth from a representative nearby off-slope location (for evaluating simulation results for configuration 1) as well as on-slope snow depth measured using grooming devices (for evaluating simulation results for the snowmaking-enabled configurations) are included in the results (where available).

For the figures shown in this section, one representative resort was chosen for each snowpack model: Obergurgl for AMUNDSEN (Fig. 6), Les Saisies for Crocus (Fig. 7), and Arosa-Lenzerheide for SNOWPACK/Alpine3D (Fig. 8). Results for the remaining resorts are shown in Appendix A.

It should be emphasized that when interpreting the snow depth time series, the differences in density of groomed vs. ungroomed snow must be taken into account. As the figures show, snow depth of ungroomed locations are often comparable or even exceed snow depth of areas covered by snowmaking, despite the latter corresponding to a significantly higher snow mass.

As shown in the line plots, natural snow accumulation is, especially in early winter, vastly different in the two considered seasons. In 2017/18 for several of the resorts natural snow depth exceeds 1 m (corresponding to > 50 cm after grooming) already in early December, while in 2016/17 despite some early snowfalls in November the slopes are practically snow free until the end of December in some resorts, only receiving noteworthy natural snowfalls from January onwards.

Results of configuration 2 (groomed natural snow) reflect the parameter settings of the grooming modules. For shallow snowpacks in the early season, results of configuration 1 and 2 are identical as grooming in the models is only performed for snowpacks reaching a certain minimum SWE or depth (as specified by the GH parameter). As soon as this threshold is exceeded the daily grooming schedule is performed, resulting in a marked decrease in snow depth due to the increased compaction.

Results of the model runs for the snowmaking-enabled configurations are shown in the figures in form of the mean over all configurations and the range (min–max), shown as solid orange lines and shaded bands, respectively. The results show that in both seasons first snow production generally starts in early to mid-November in most resorts, i.e., as soon as temperatures are low enough to allow production. Each snow gun then produces snow until the specified production target (in the case of AMUNDSEN and Crocus) or snow depth threshold (in the case of SNOWPACK/Alpine3D) is reached. Especially in the 2016/17 season, due to lacking natural snowfalls in most resorts snow depth is still below the preset threshold (60 cm) at the start of the reinforcement period (16 December) for all configurations, thus production is resumed starting from this date as soon as the ambient conditions allow it and depending on if water is available. In some resorts (e. g., Garmisch Classic/Zugspitze), snow is then still sporadically produced throughout January in order to maintain the 60 cm threshold. In 2017/18, large natural snowfalls occur especially during December and January, with peak (natural) SWE amounts almost quadrupling compared to the previous season in some resorts. Hence, during this season snow production is completely stopped after the base-layer period in most cases. This also explains the differences in the spread of the simulation results for the different management configurations (orange shaded areas in the line plots) between the two seasons: for most resorts the spread generated by the different configurations converges into a single line after the base-layer period in 2016/17, whereas in 2017/18 there is still some variation between the configurations. Since in 2016/17 snow depth is still below the 60 cm threshold after the end of the base-layer period, in the reinforcement period for all configurations snow is produced until exactly 60 cm are reached, thus resulting in the same snowpack evolution for all configurations for the remainder of the season (since no more snow is produced afterwards). In 2017/18, due

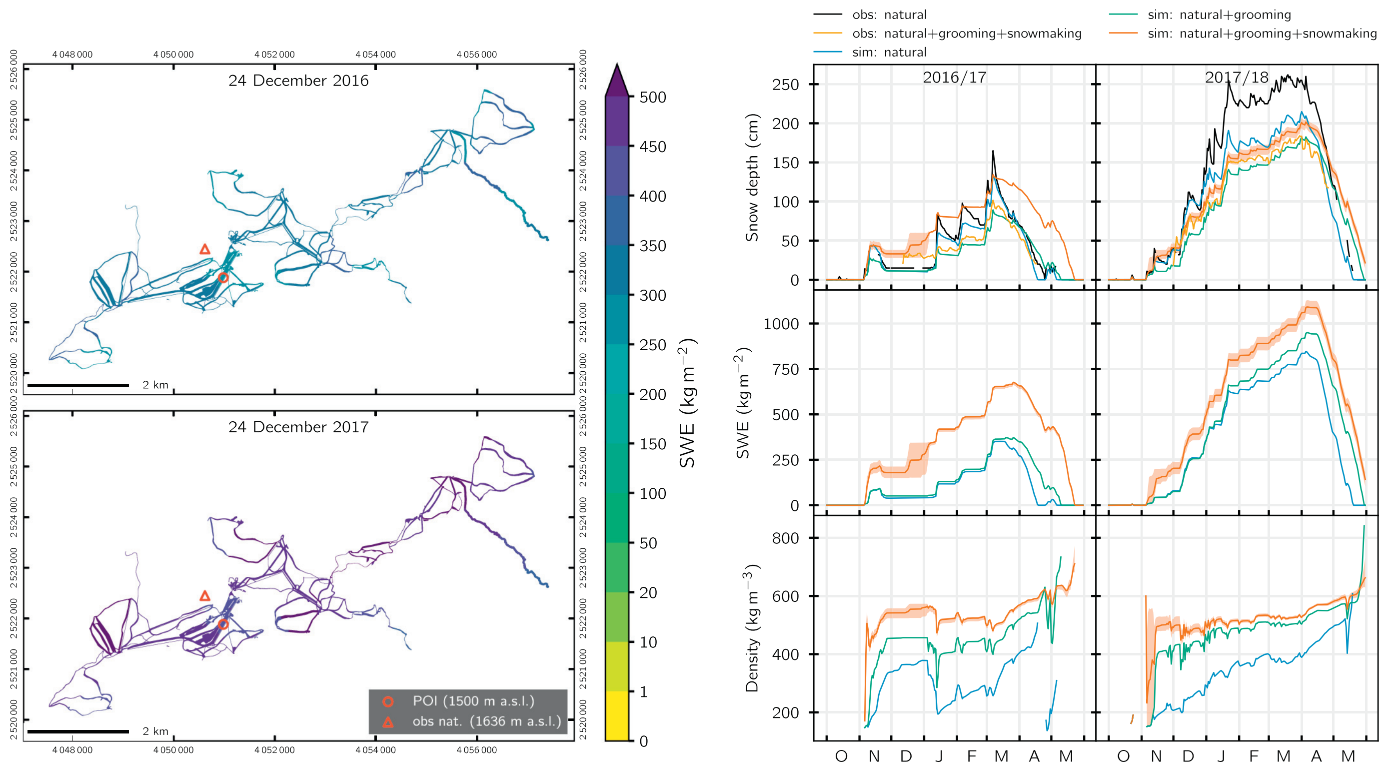

Fig. 7. Crocus simulation results for the Les Saisies ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the SRUs covered by snowmaking configuration 23 was used, remaining SRUs were subject to grooming only). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1500 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed natural snow depth from a nearby location (indicated with a red triangle in the maps) as well as observed on-slope snow depth are shown in black and yellow, respectively.

to more natural snowfall the 60 cm threshold is already exceeded during the base-layer period, hence the only snow production in this season is due to the fixed base-layer production volumes (150 and 250 kg m^{-2} – i. e., after the base-layer period the spread shown in the line plots actually consists only of two distinct lines corresponding to these values).

Comparison of the available natural snow depth observations (black lines in the figures) with the simulation results shows that the natural snow depth evolution for the given locations is reasonably well reproduced by the models. This is confirmed by the quantitative evaluation of model performance for natural snow, shown in the left part of Table 7. Here, model performance in reproducing natural snow evolution for the selected points is evaluated using three efficiency criteria: the coefficient of determination R^2 (range between 0 and 1, higher values are better), the Kling-Gupta efficiency KGE (range between $-\infty$ and 1, higher values are better), and the bias (i. e., the average tendency of the simulated values to be larger (resulting in positive bias values) or smaller (negative values) than the observations). The values in Table 7 were calculated for the two considered seasons (Oct–May 2016/17 and 2017/18) where possible. While the temporal availability of observations differs between the resorts and the values are hence not directly comparable (e. g., for La Plagne only very few observations are available (Fig. A.12)), for all resorts a satisfactory model performance in terms of natural snow depth is revealed.

The same efficiency criteria were calculated for the on-slope locations using snow depth measurements from grooming devices and the simulation results for the eight snowmaking-enabled snow management configurations. Deviations between the observed and simulated snow depths do not reflect model deficiencies, but the comparison rather shows to which degree the generic set of snow management configurations as presented herein might be applicable for the individual ski resorts. However, both the visual comparison in the result figures and the computed model efficiency values in the right side of Table 7 show that in several cases even these generic model configurations lead to very satisfactory simulation results for the selected points.

Finally, in the maps showing the spatially distributed model output for 24 December, the differences between the two seasons are again clearly visible, showing large natural snow amounts in 2017 and – for several resorts – virtually snow-free mountains in 2016. For the ski slopes, the areas equipped by snowmaking facilities can be clearly distinguished from slopes covered by natural snow only. While in some resorts (e. g., Lenzerheide and Livigno) only few slopes are covered by snow guns as visible in the results, several other resorts have near-full snowmaking coverage. Simulated SWE amounts on slopes covered by snowmaking are considerably larger and more homogeneous due to the set production targets or snow depth thresholds in the base-layer period, ensuring that production is stopped as soon as the respective snow amounts have been produced or the defined snow depth has been reached.

6. Conclusions and outlook

The initiative for this study emerged within the H2020 PROSNOW project, where a forecasting system for snow conditions in ski resorts based on meteorological forecasts and snowpack modeling is being developed. While the snowpack models AMUNDSEN and Crocus were already equipped with snow management modules presented in previous studies, as part of the work in PROSNOW a new snow management scheme was integrated into SNOWPACK/Alpine3D. These three implementations now represent the state of the art of the integration of snow management processes in physically based snowpack models. While the specific implementations differ to some degree between the

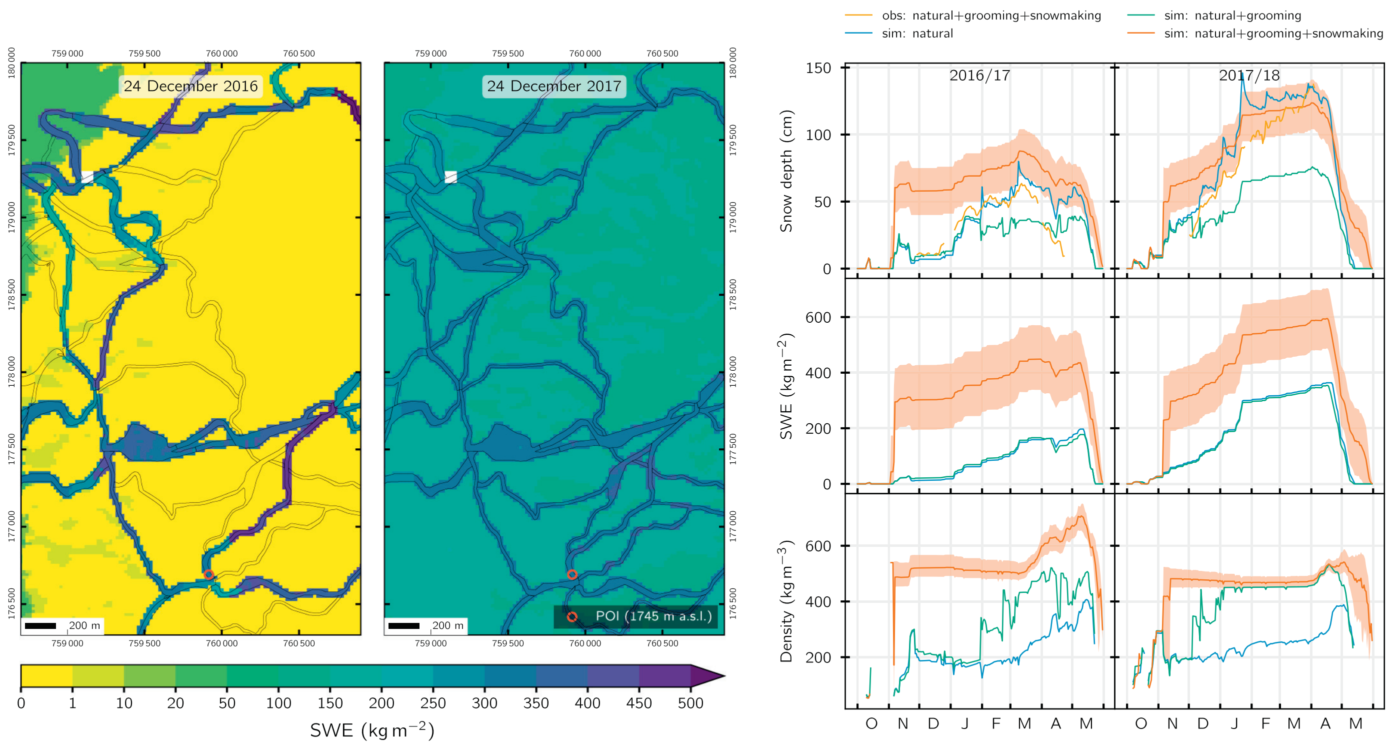

Fig. 8. SNOWPACK/Alpine3D simulation results for the Lenzerheide ski resort. Maps (displaying only parts of the resort for visualization purposes) show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1745 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed on-slope snow depth is shown in yellow.

Table 7
Model efficiency criteria (coefficient of determination R^2, Kling-Gupta efficiency KGE, and bias) calculated using observed and simulated natural snow depth as well as observed and simulated on-slope snow depth (for the latter, mean as well as minimum and maximum values over the eight snowmaking-enabled configurations are listed) for the seasons 2016/17 and 2017/18. Temporal availability of observation data varies among the resorts. For Garmisch Classic/Zugspitze and Livigno, neither natural nor on-slope snow depth observations were available.

	Natural snow			Managed snow		
	R^2	KGE	Bias	R^2	KGE	Bias
Arosa-Lenzerheide				0.95 (0.94–0.96)	0.42 (0.22–0.64)	0.40 (0.09–0.68)
Colfosco	0.91	0.84	−0.03	0.78 (0.76–0.80)	0.58 (0.49–0.66)	−0.10 (−0.18–−0.03)
La Plagne	0.96	0.75	0.23			
Les Saisies	0.99	0.72	−0.19	0.87 (0.84–0.90)	0.71 (0.68–0.75)	0.27 (0.22–0.31)
Obergurgl	0.98	0.80	0.16	0.49 (0.48–0.49)	−0.09 (−0.10–−0.07)	−0.06 (−0.11–−0.00)
San Vigilio				0.94 (0.93–0.94)	0.06 (0.04–0.08)	−0.34 (−0.45–−0.26)
Seefeld	0.95	0.75	0.21	0.87 (0.87–0.87)	0.59 (0.57–0.61)	0.15 (0.07–0.22)

models, all three share a certain set of core parameters that can be used to adapt the models to resort-specific practices. These implementations allow for a very detailed simulation of snow management practices in the three modeling systems, taking into account snow demand (being largely influenced by socioeconomic considerations), the meteorological conditions in terms of wet-bulb temperature and wind speed, and the ski resort infrastructure that ultimately determines the amount of snow that can actually be produced in a given time step. The implemented grooming schemes allow to account for the distinct properties of groomed snow on ski slopes depending on the amount of snow present and a defined grooming schedule.

To provide ski resort representatives with a range of possible future snowpack states depending on their management choices, a set of default model configurations has been prepared that can be further refined for each ski resort and subsequently be used for the operational simulations.

For the results presented in this study, the models were set up for all nine pilot ski resorts. Simulation runs were performed for two contrasting seasons: the very dry 2016/17 season and the snow-rich 2017/18 season. All ten strategic snow management configurations (ungroomed natural snow, groomed natural snow, and eight snowmaking-enabled configurations) were used for the presented results, allowing to demonstrate the models' capabilities to reproduce the observed natural snow evolution, and to show the functionality of the snowmaking and grooming modules based on the selected parameters.

It should be emphasized that the results of the snow production runs do not reflect the actual snow management practice for these seasons in the individual ski resorts, but are rather solely intended to demonstrate the functionality of the snow management modules. The same snow management configurations were chosen for all ski resorts in order to ensure comparability of the model results between the different resorts. In reality, management practices between the resorts might vary widely, and both the fixed model parameters and the set of model configurations will have to be refined accordingly for each resort.

However, the presented approaches for simulating snow management also have some limitations, which become partly visible in the presented comparison of the observed and simulated snow depths on the slopes. On the one hand, obviously the presented assumptions for the decision when and where snow should be produced and when the slopes should be groomed are highly simplified and cannot be expected to be an accurate depiction of reality. The presented approach to run the models with different management configurations is one attempt to account for these simplifications and present the end users of the modeling chain with a range of possible snowpack evolutions. The accuracy of the model results is in this case highly dependent on the involvement of the stakeholders, i. e., to which degree the real-world snow management practice can be translated to the model implementations (Strasser et al., 2014). On the snowpack modeling side, one major assumption in all three model implementations is that for a given snow gun all of the produced snow is distributed immediately and evenly over a predefined slope section, and that grooming has no effects on the distribution of snow but rather only compacts it. In practice, snow is heavily redistributed on a daily basis both due to skier movements and due to grooming operations (involving both moving snow from slope locations to other slope locations as well as moving natural snow from off-slope locations to the slopes). Furthermore, snowmaking losses due to thermodynamic and mechanical effects are currently only represented using a fixed water loss factor in the models. In practice, these losses are highly variable depending on meteorological conditions and other factors such as the exact positioning of the snow guns depending on current wind conditions (which determines if wind-blown snow is transported to off-slope locations and is actually "lost", or if it is transported to other parts of the slopes or off-slope locations where it can be easily recovered). Third, the assumption that snow guns are assigned to fixed locations is often not true in reality, where frequently at least part of the snow guns are mobile and moved around during the season, depending on where snow is currently required.

Since many of these processes currently cannot be reasonably represented in a numerical model, deviations between the real snow conditions on the slopes and those simulated by the models are unavoidable. Hence, for operational model applications such as envisaged in the PROSNOW project, it is crucial to integrate local observations (water consumption recordings from the snow guns and distributed snow depth measurements from groomers) in order to be able to produce reliable forecasts. Future work will focus on updating model states by assimilating these local observations, as well as evaluating the snowpack simulations driven by meteorological forecasts. 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). The next steps of the PROSNOW project, which are beyond the scope of this paper and will be explored in future works, will first consist of using forecast products to drive the snow simulations with an ensemble of meteorological members, in order to anticipate the future conditions of the snowpack on the ski slopes, which is the main interest of the PROSNOW project. In addition, local measurements of water consumption for snowmaking and snow depth on the ski slopes will be inserted in the modeling chain, to improve the description of the initial state of the snowpack before running the forecast simulations. Subsequently, the performances of the models will be evaluated by comparing model outputs with local and remotely-sensed measurements, not only in terms of snow depth and SWE, but also looking at other variables such as the amount of water consumed for snowmaking over the season.

Finally, while in this paper each ski resort was simulated only with one single snowpack model, from the model development perspective an intercomparison of the three snowpack models being applied to the same resort(s) would be a logical next step. Differences in the simulation results of the three models for a given location would be mainly due to different approaches in the simulation of snow management on the one hand and the different approaches for simulating the snowpack energy and mass balance on the other hand. For a reasonable comparison these effects would have to be disentangled and discussed accordingly, which is not straightforward and out of scope for this paper but which we will consider for the future. Rather, here we have shown that all three models are able to produce plausible and robust results on the ski slope scale, and that the accuracy of the results is mainly dependent on the degree to which the real-world snow management practices are integrated.

Data availability

Datasets related to this article can be found at https://doi.org/10.5281/zenodo.3564236 (Hanzer et al., 2019).

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Pirmin Philipp Ebner: Software, Resources, Writing - Reviewing and Editing

Franziska Koch: Software, Resources, Writing - Reviewing and Editing

Fabiano Monti: Resources

Mathias Bavay: Software

Matthias Bernhardt: Supervision

Matthieu Lafaysse: Software

Michael Lehning: Supervision, Writing - Reviewing and Editing

Ulrich Strasser: Conceptualization, Methodology, Supervision, Writing - Reviewing and Editing

Hugues François: Software, Resources

Samuel Morin: Conceptualization, Methodology, Supervision, Writing - Reviewing and Editing, Funding acquisition

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Appendix A. Further results

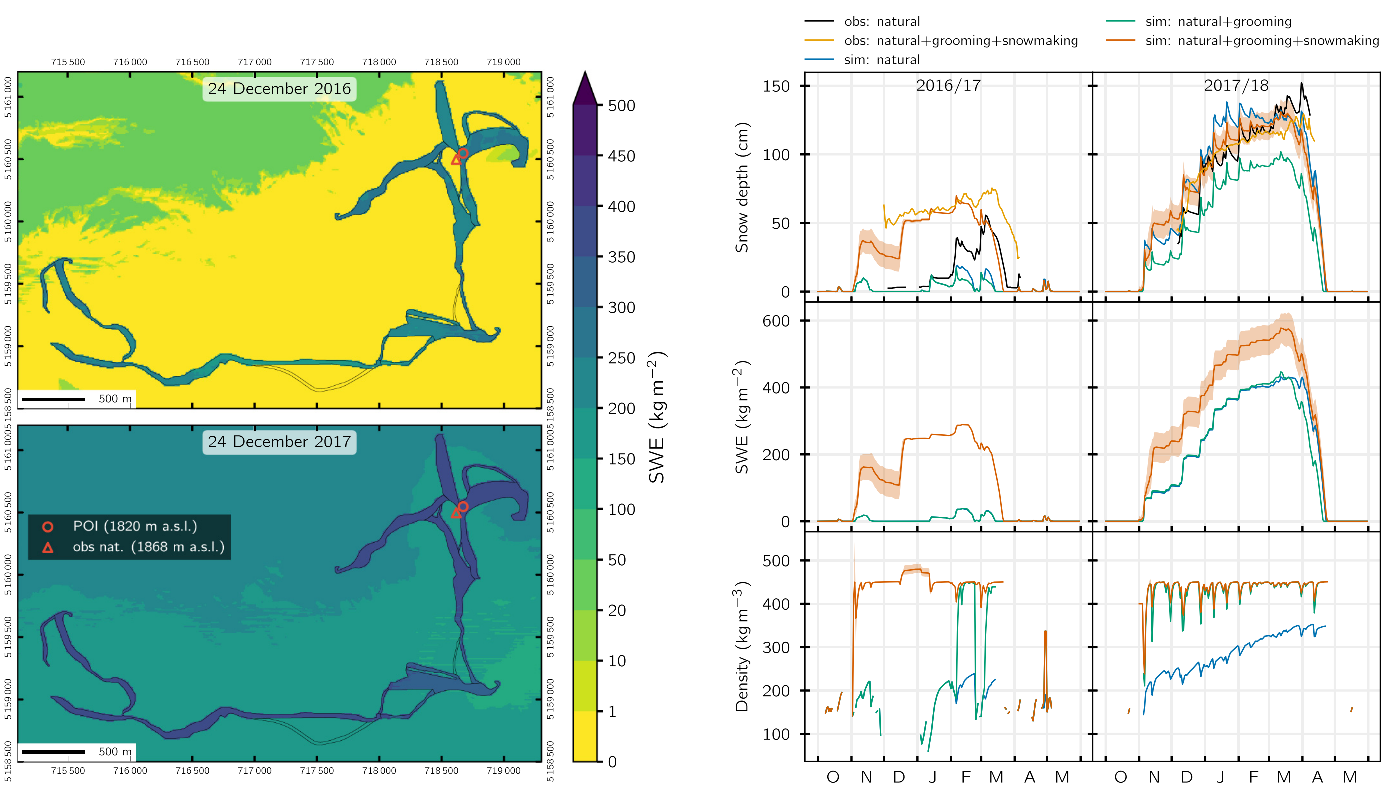

Fig. A.9. AMUNDSEN simulation results for the Colfosco ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1820 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed natural snow depth from a nearby location (indicated with a red triangle in the maps) as well as observed on-slope snow depth are shown in black and yellow, respectively.

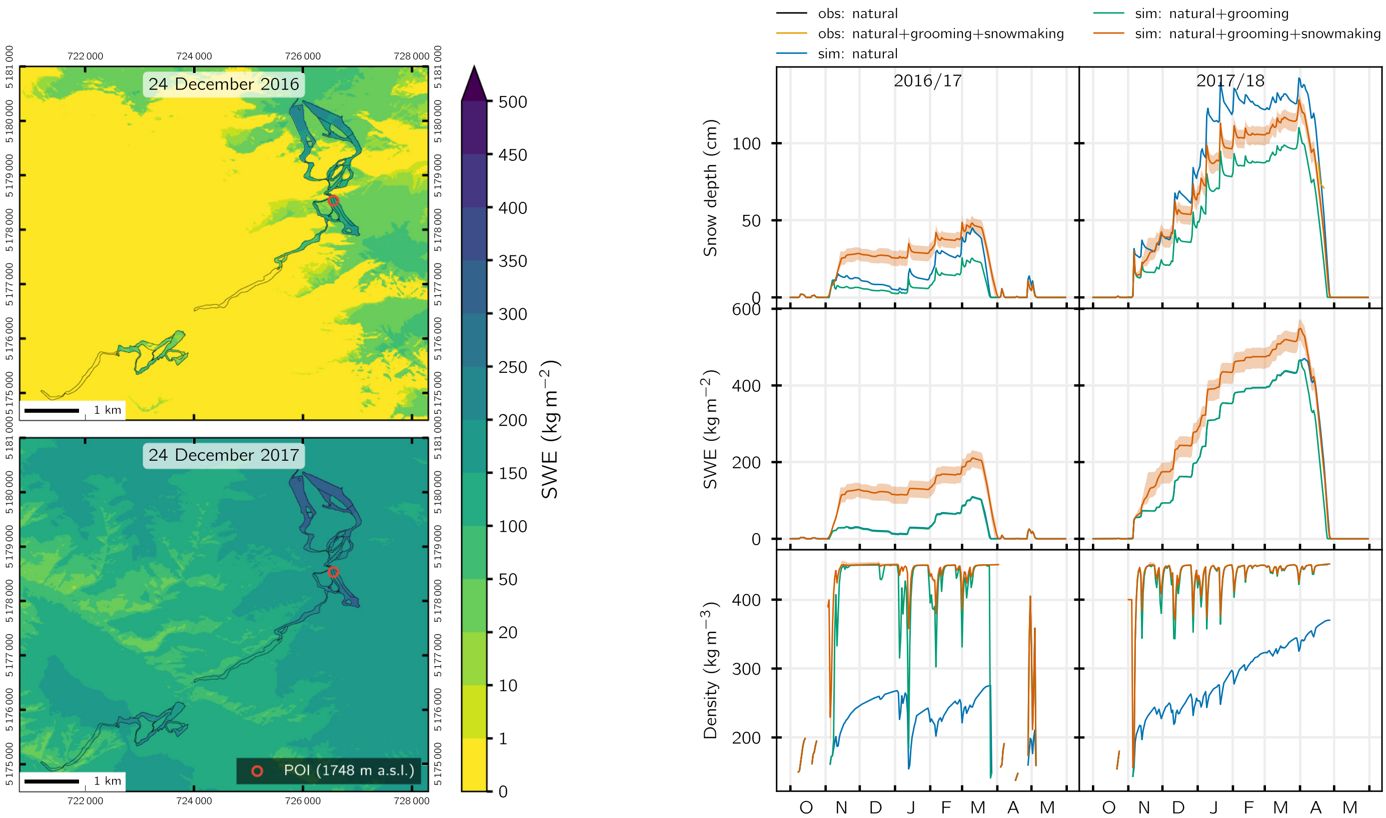

Fig. A.10. AMUNDSEN simulation results for the San Vigilio ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1748 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed on-slope snow depth is shown in yellow.

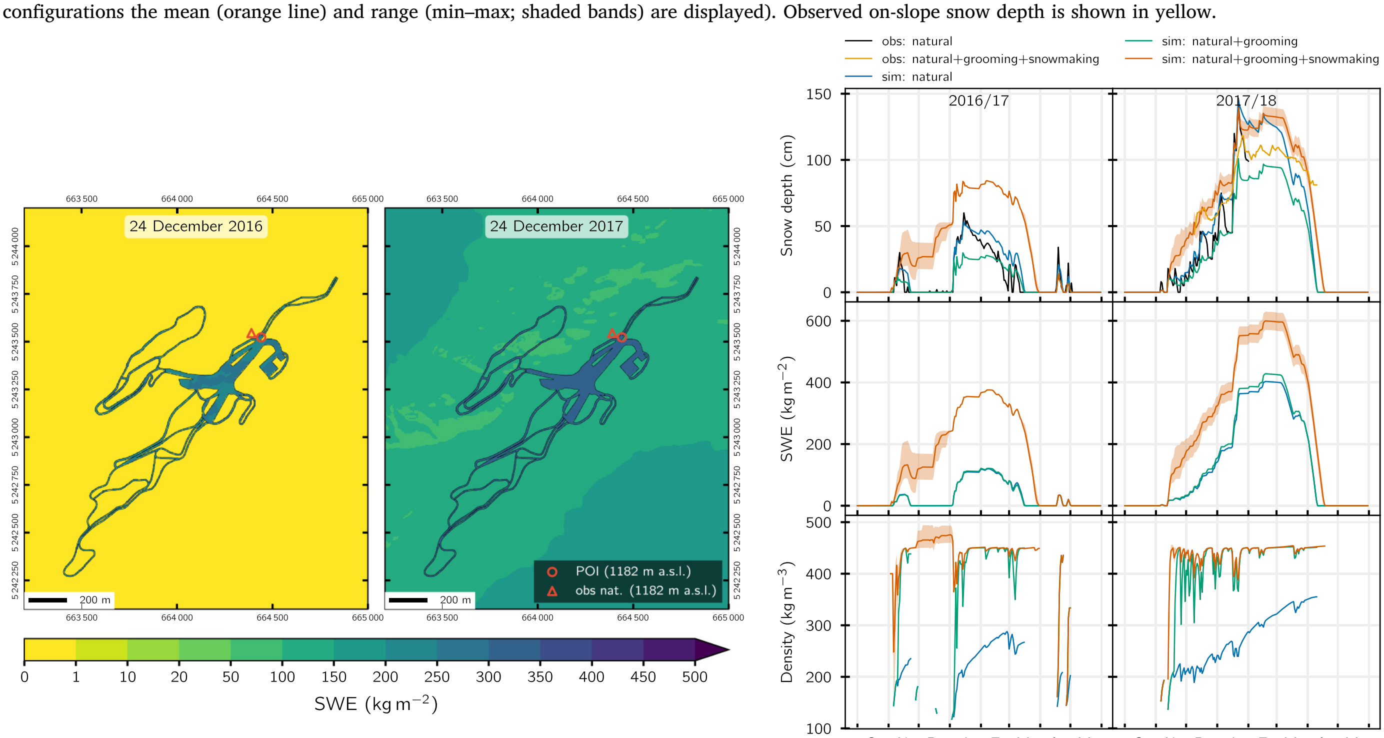

Fig. A.11. AMUNDSEN simulation results for the Seefeld cross-country ski resort (2019 Nordic World Ski Championships tracks only). Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the ski tracks (all covered by snowmaking) configuration 23 was used, off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a track location at 1182 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed natural snow depth from a nearby location (indicated with a red triangle in the maps) as well as observed on-slope snow depth are shown in black and yellow, respectively.

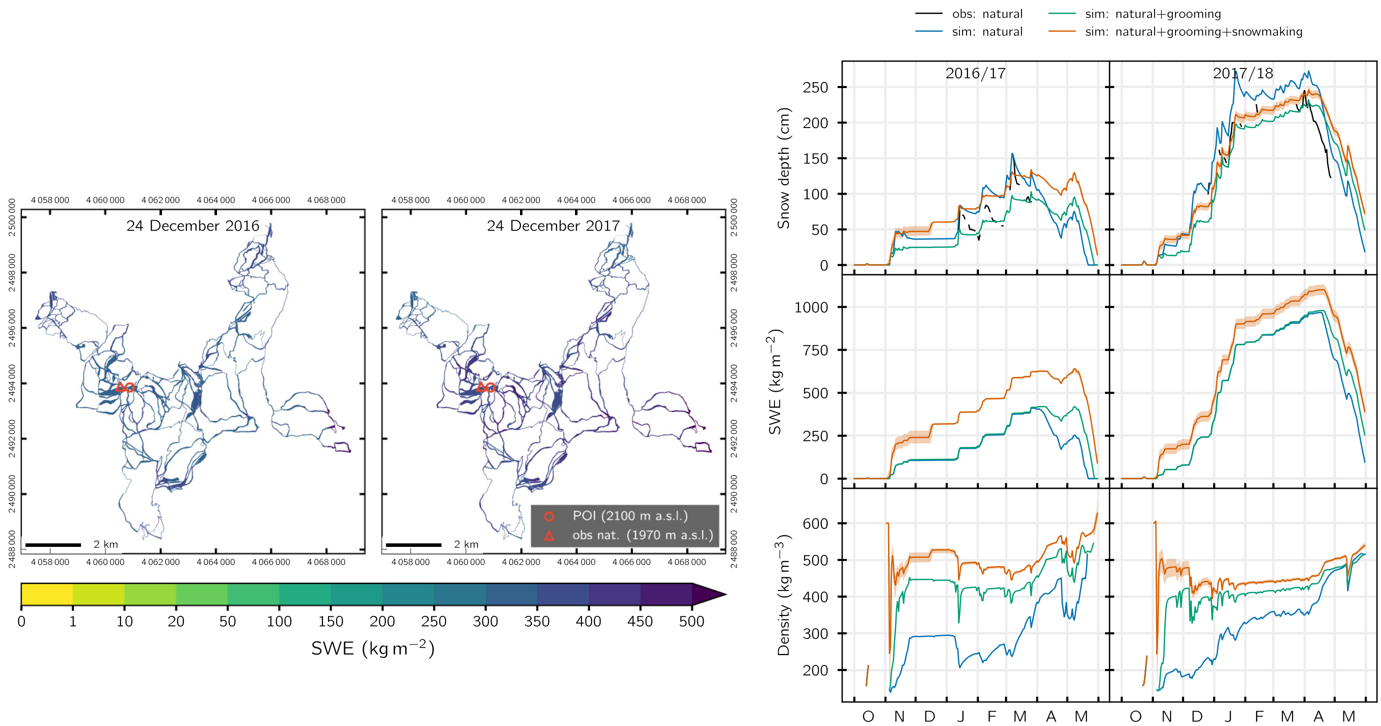

Fig. A.12. Crocus simulation results for the La Plagne ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the SRUs covered by snowmaking configuration 23 was used, remaining SRUs were subject to configuration 2, i. e., grooming only). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 2100 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed). Observed natural snow depth from a nearby location (indicated with a red triangle in the maps) is shown in black.

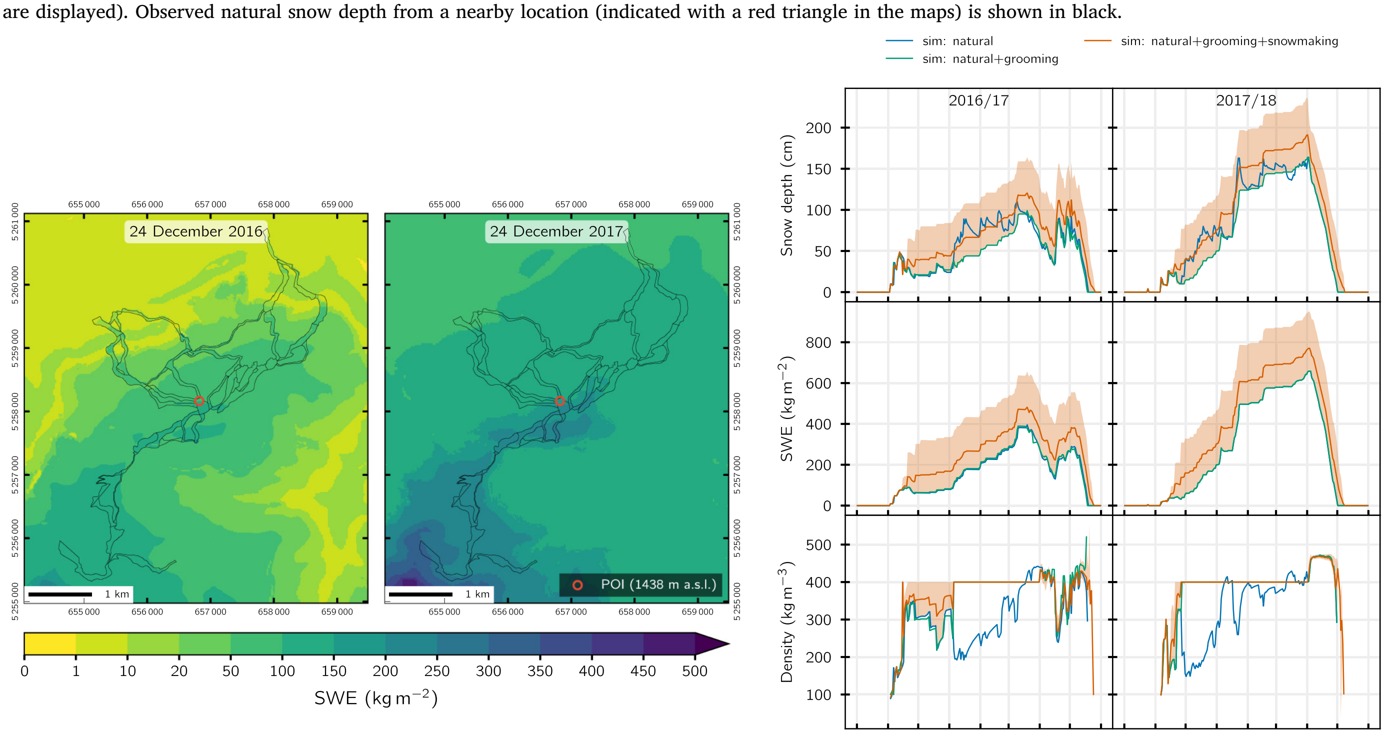

Fig. A.13. SNOWPACK/Alpine3D simulation results for the Garmisch Classic/Zugspitze ski resort. Maps show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 1438 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed).

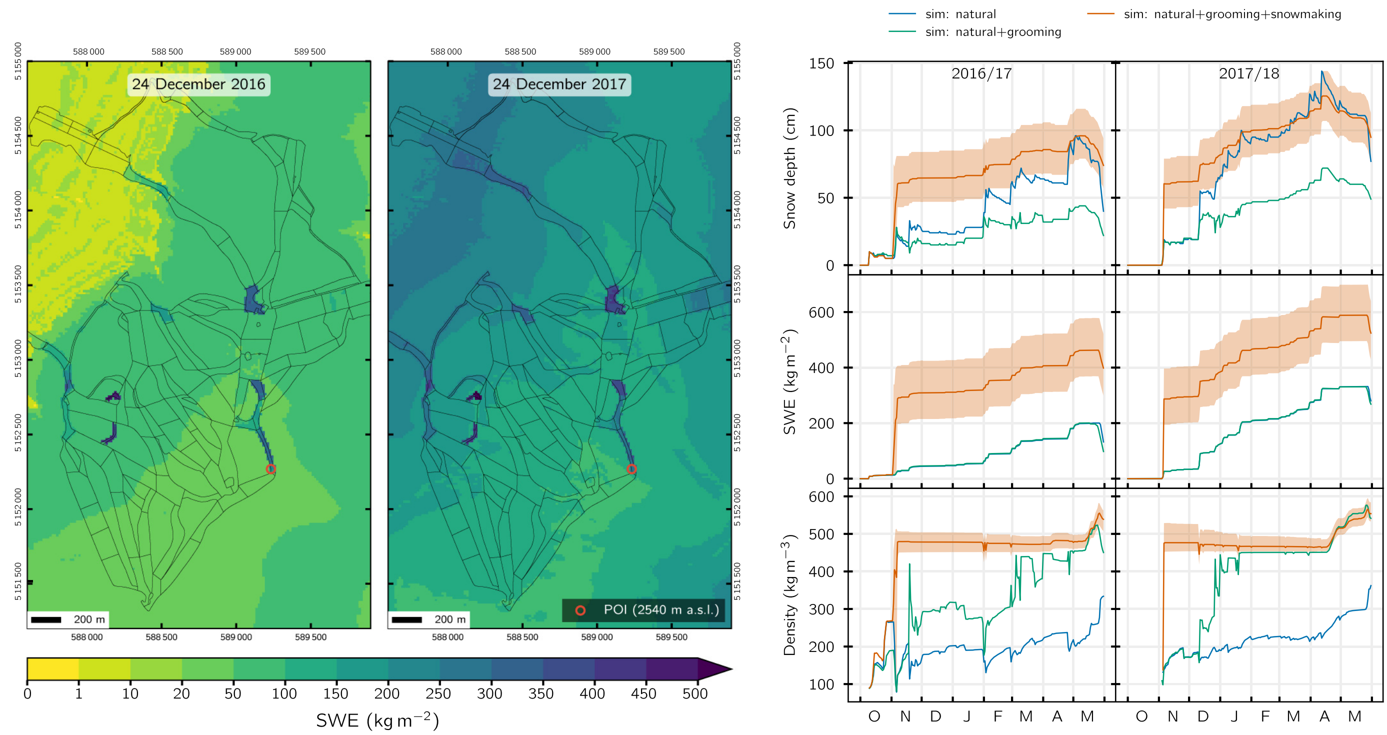

Fig. A.14. SNOWPACK/Alpine3D simulation results for the Livigno ski resort. Maps (displaying only parts of the resort for visualization purposes) show the simulated SWE distribution for 24 December 2016 and 2017 (for the slope sections covered by snowmaking configuration 23 was used, remaining slope sections were subject to grooming only, and off-slope areas show natural snow simulation results). Line plots show snow depth (top), SWE (center), and density (bottom) evolution for a slope location at 2540 m a.s.l. (indicated with a red circle in the maps) for the seasons 2016/17 and 2017/18 and the ten strategic snow management configurations according to Fig. 5 (for the eight snowmaking-enabled configurations the mean (orange line) and range (min–max; shaded bands) are displayed).

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