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Provision of a prediction system allowing for management and optimization of snow in Alpine ski resorts

Process-based simulation of snow cover evolution in ski resorts using the AMUNDSEN model: results and validation

Florian Hanzer, Daniel Günther, Ulrich Strasser, Valentina Premier, Mattia Callegari, Carlo Marin, Claudia Notarnicola

EGU 2020, 7 May 2020

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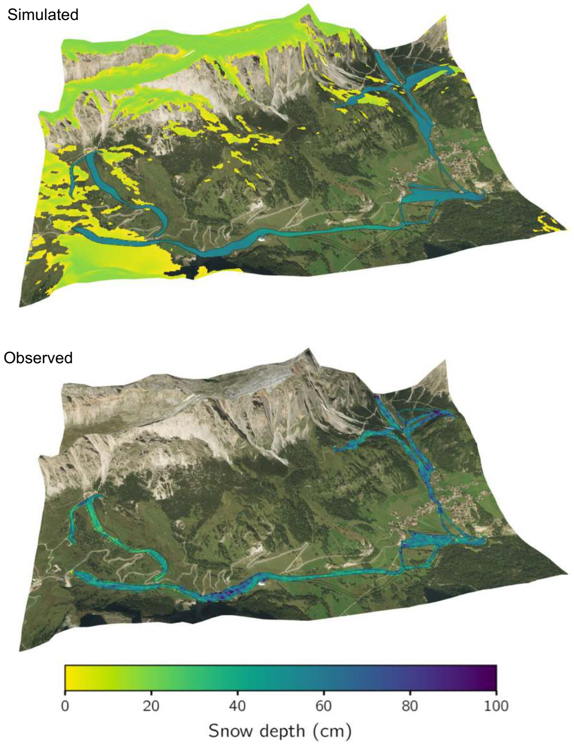
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No730203

Snow management modeling

- Physically based snowpack models allow simulation of the (natural) snow cover
- For the application in ski resorts, snow management processes (snowmaking and grooming) must be considered
  - Physical component: description of the snowmaking and grooming processes
  - Socioeconomic component: when, where, and how much to produce



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- H2020 project aiming at developing an operational forecasting system for snow conditions in ski resorts
- Time scales from **days** until several **months** ahead

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Snow models in PROSNOW

	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	30 min–24 h
Meteorological preprocessing	Built-in	Often associated with SAFRAN (Durand et al., 1993)	MeteoIO (Bavay and Egger, 2014)

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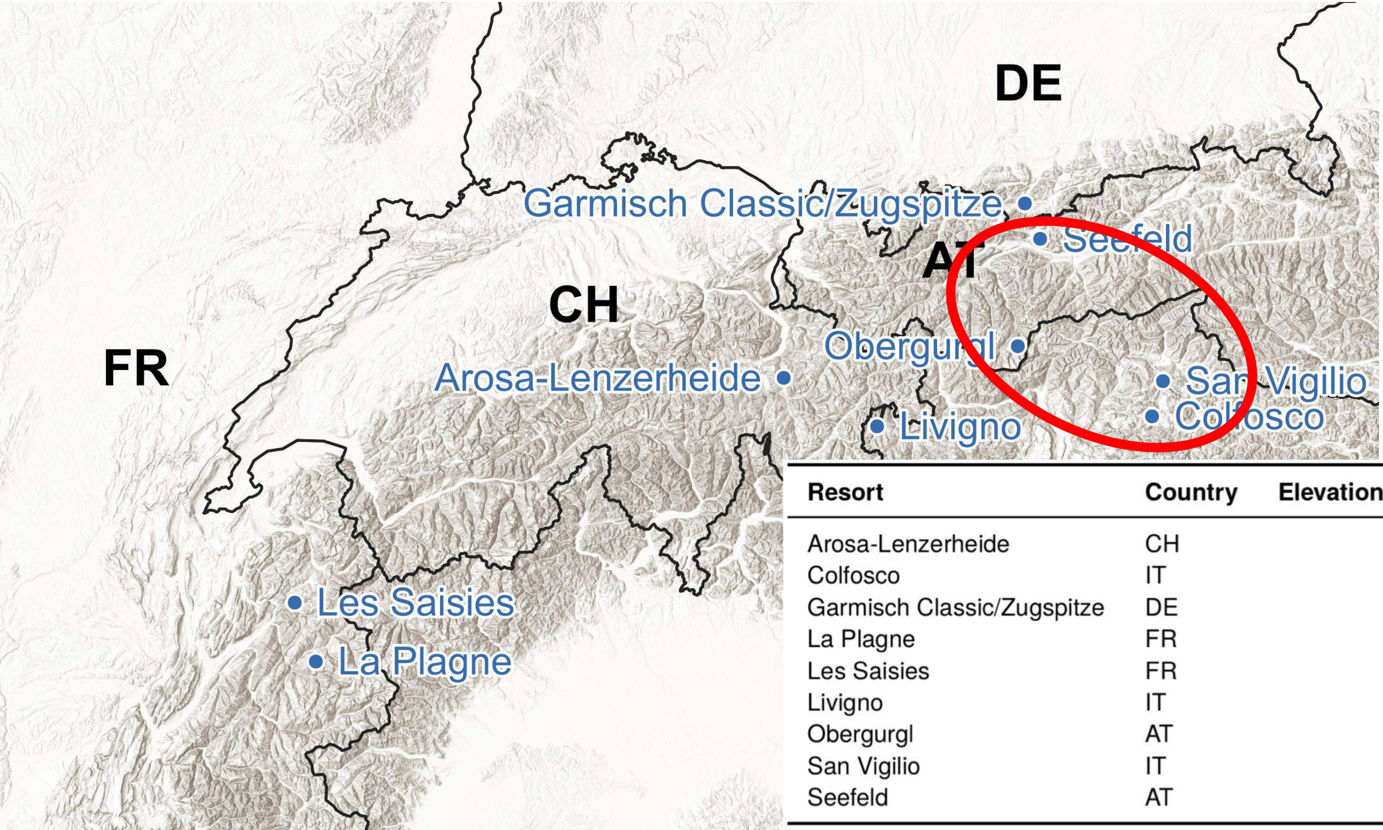
Pilot ski resorts



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

Snow production parameters

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	cm		Snow depth threshold for stopping production during the base-layer period	–	–	×
Reinforcement snow threshold	ST_r	cm		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	$m^3\,h^{-1}\,°C^{-1}$	Snow gun type	First parameter of Equation (1) to calculate the water flow rate for a single snow gun	×	×	×
Production rate parameter 2	PR_b	$m^3\,h^{-1}$	Snow gun type	Second parameter of Equation (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	$m^3\,h^{-1}$		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	–	×	×

Snow demand

- Is there a need for producing?

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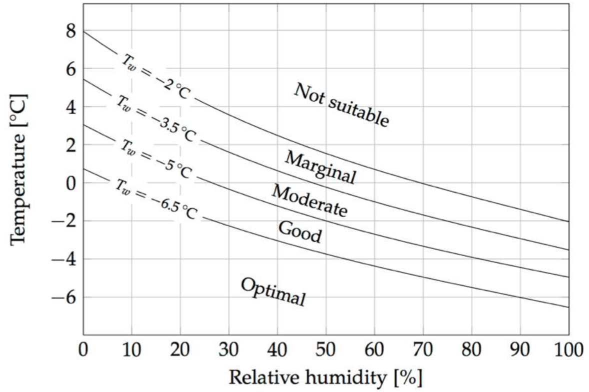
Snow production parameters

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	cm		Snow depth threshold for stopping production during the base-layer period	–	–	×
Reinforcement snow threshold	ST_r	cm		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	$m^3\,h^{-1}\,°C^{-1}$	Snow gun type	First parameter of Equation (1) to calculate the water flow rate for a single snow gun	×	×	×
Production rate parameter 2	PR_b	$m^3\,h^{-1}$	Snow gun type	Second parameter of Equation (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	$m^3\,h^{-1}$		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	–	×	×

Ambient conditions

- Air temperature
- Humidity
- Wind speed



Adapted from Hofstätter (2008)

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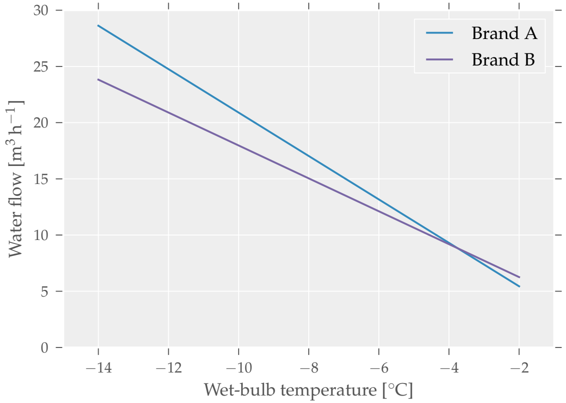
Snow production parameters

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	cm		Snow depth threshold for stopping production during the base-layer period	–	–	×
Reinforcement snow threshold	ST_r	cm		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	$m^3\,h^{-1}\,°C^{-1}$	Snow gun type	First parameter of Equation (1) to calculate the water flow rate for a single snow gun	×	×	×
Production rate parameter 2	PR_b	$m^3\,h^{-1}$	Snow gun type	Second parameter of Equation (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	$m^3\,h^{-1}$		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	–	×	×

Infrastructure

- Snow guns
- Water availability
- Pumping capacity



Hanzer et al. (2014)

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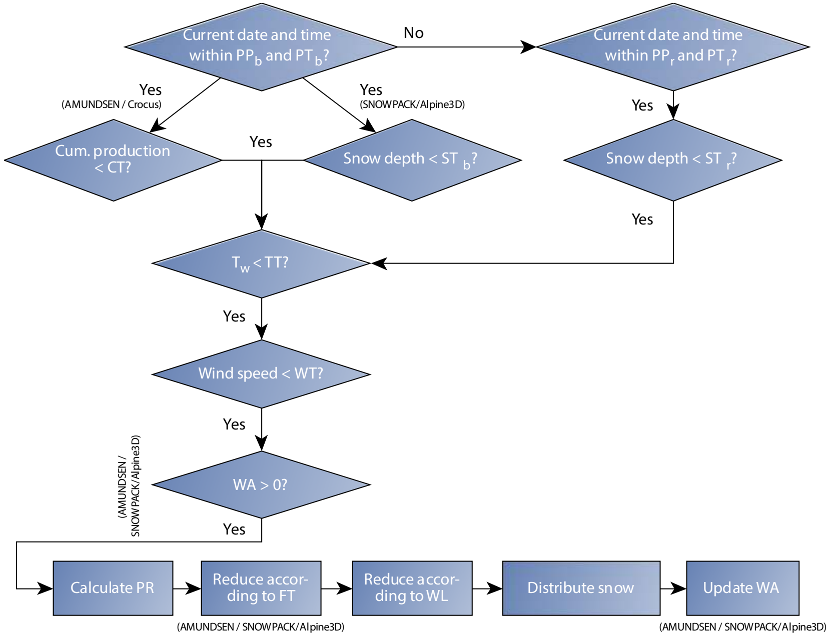
Snow production parameters

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	cm		Snow depth threshold for stopping production during the base-layer period	–	–	×
Reinforcement snow threshold	ST_r	cm		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	$m^3\,h^{-1}\,°C^{-1}$	Snow gun type	First parameter of Equation (1) to calculate the water flow rate for a single snow gun	×	×	×
Production rate parameter 2	PR_b	$m^3\,h^{-1}$	Snow gun type	Second parameter of Equation (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	$m^3\,h^{-1}$		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	–	×	×



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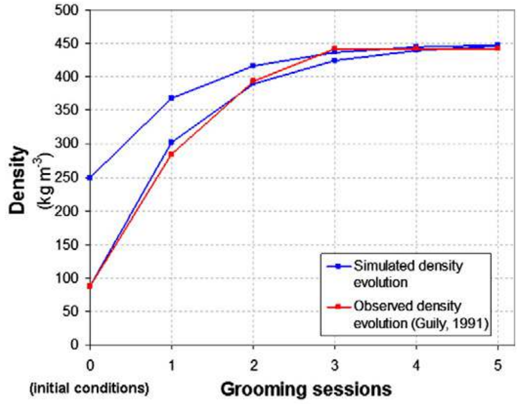
Grooming parameters

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 (AMUNDSEN/Crocus) or snow depth (SNOWPACK/Alpine3D) required for grooming	×	×	×
Penetration depth	PD	$kg\,m^{-2}$ / cm	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	–	×	–

- Explicit simulation of densification
- Implicit consideration of (re-)distribution



Spandre et al. (2016)

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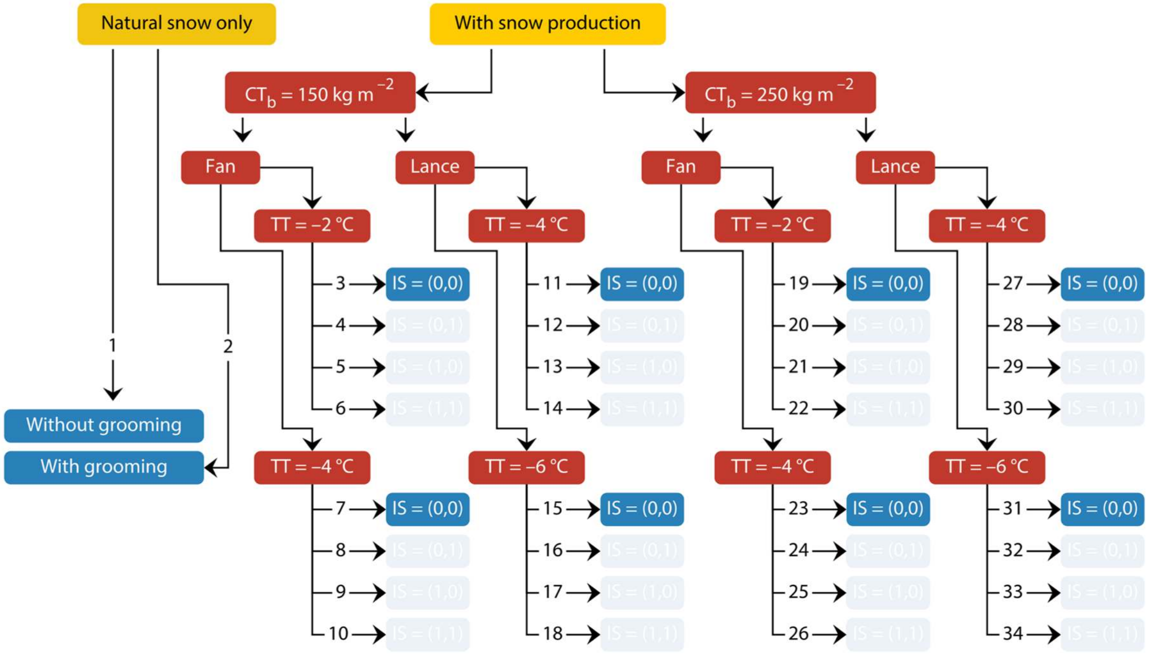
Snow management configurations

Use a range of configurations (parameter sets) to account for different snow management strategies during the season



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Validation data

Type	Temporal resolution	Spatial resolution
Snow depth from groomers	daily	3 m
Sentinel-2 snow cover maps	up to 5-daily	10 m
Recordings from snow guns (water consumption, energy consumption, wet-bulb temperature)	(sub-)hourly	point-based

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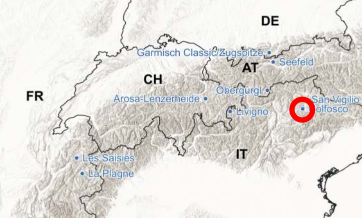
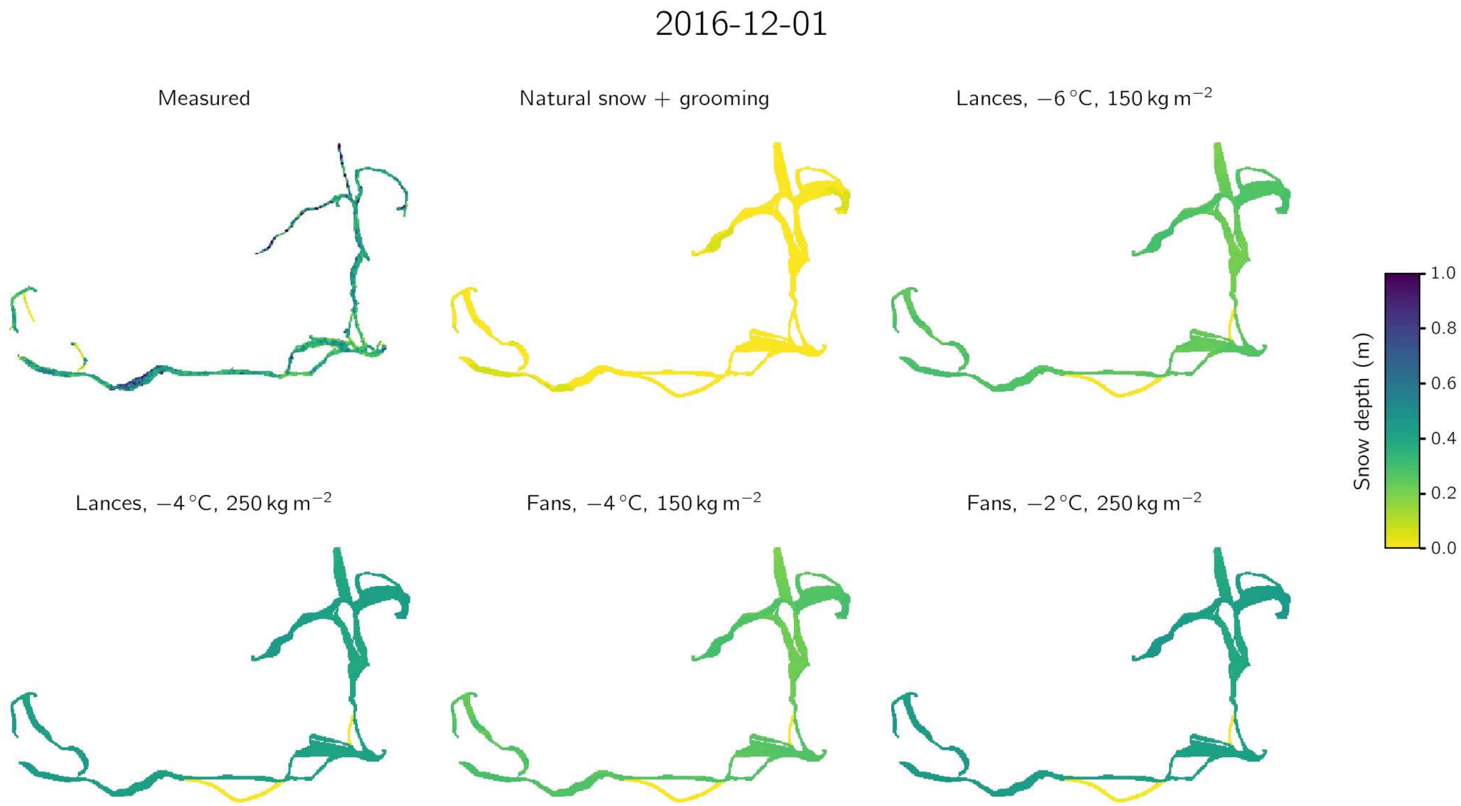
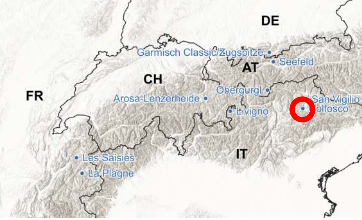
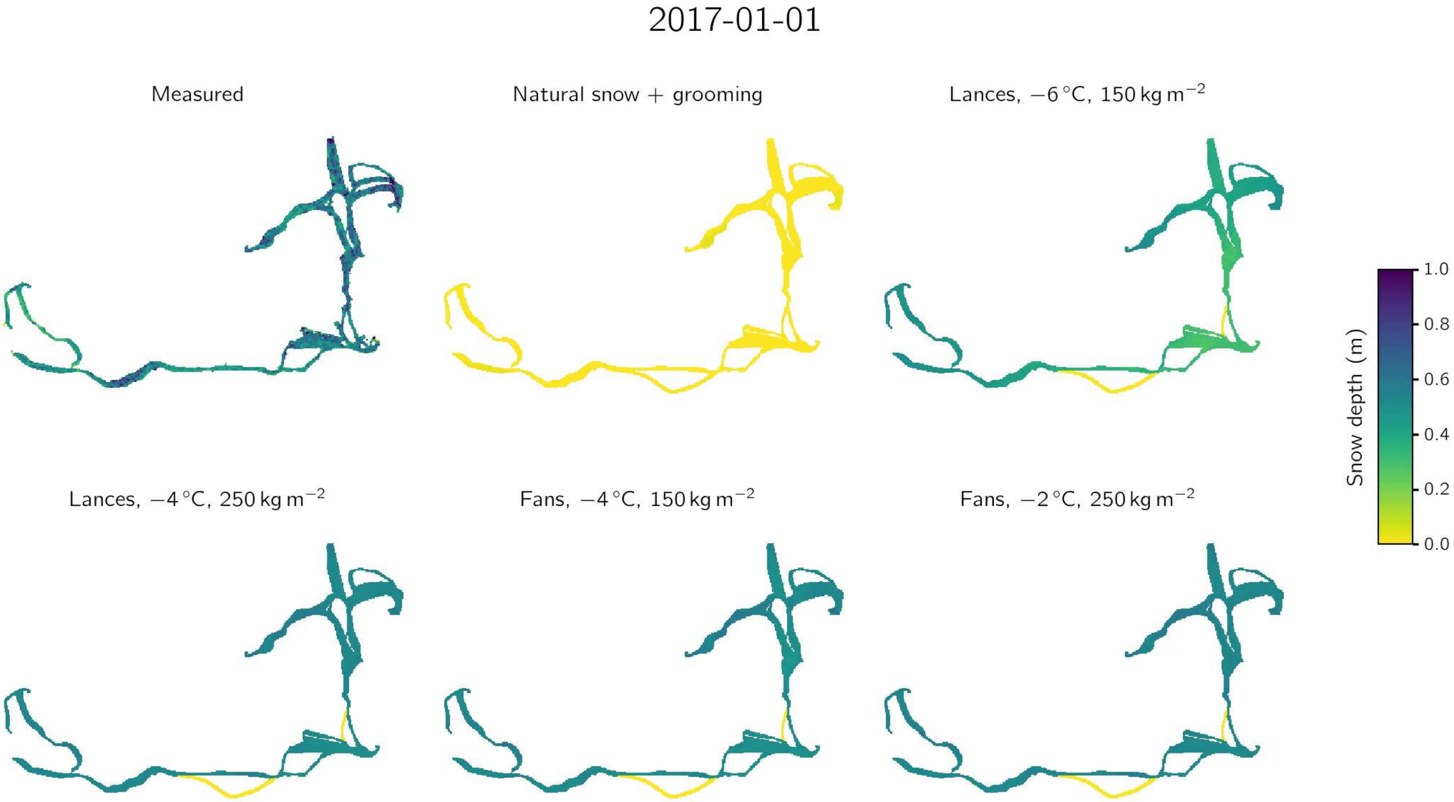
Results: snow depth



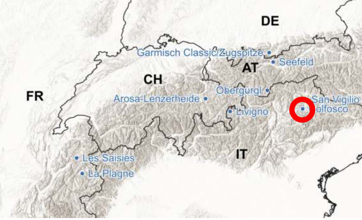


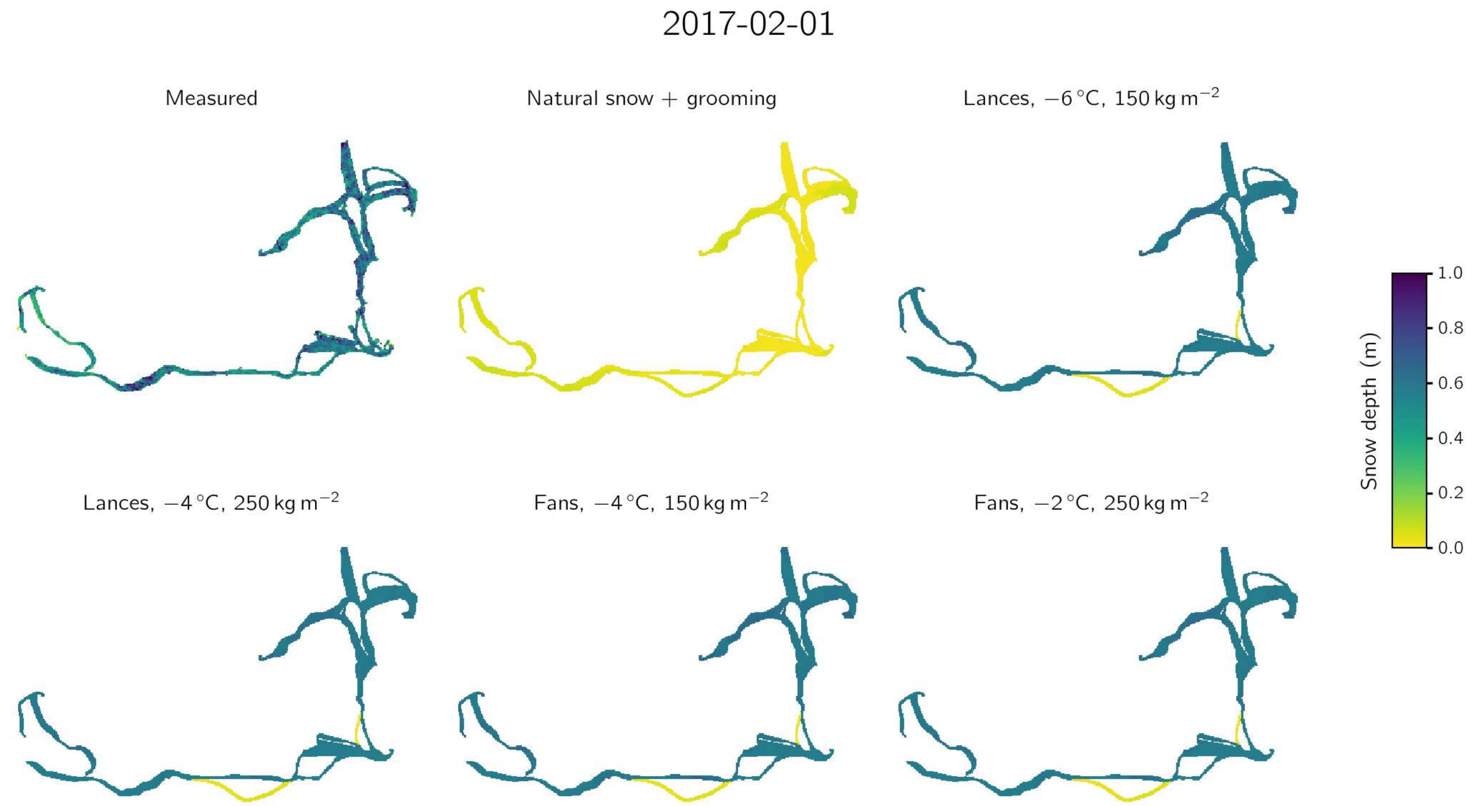
Results: snow depth



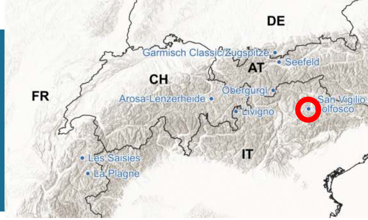


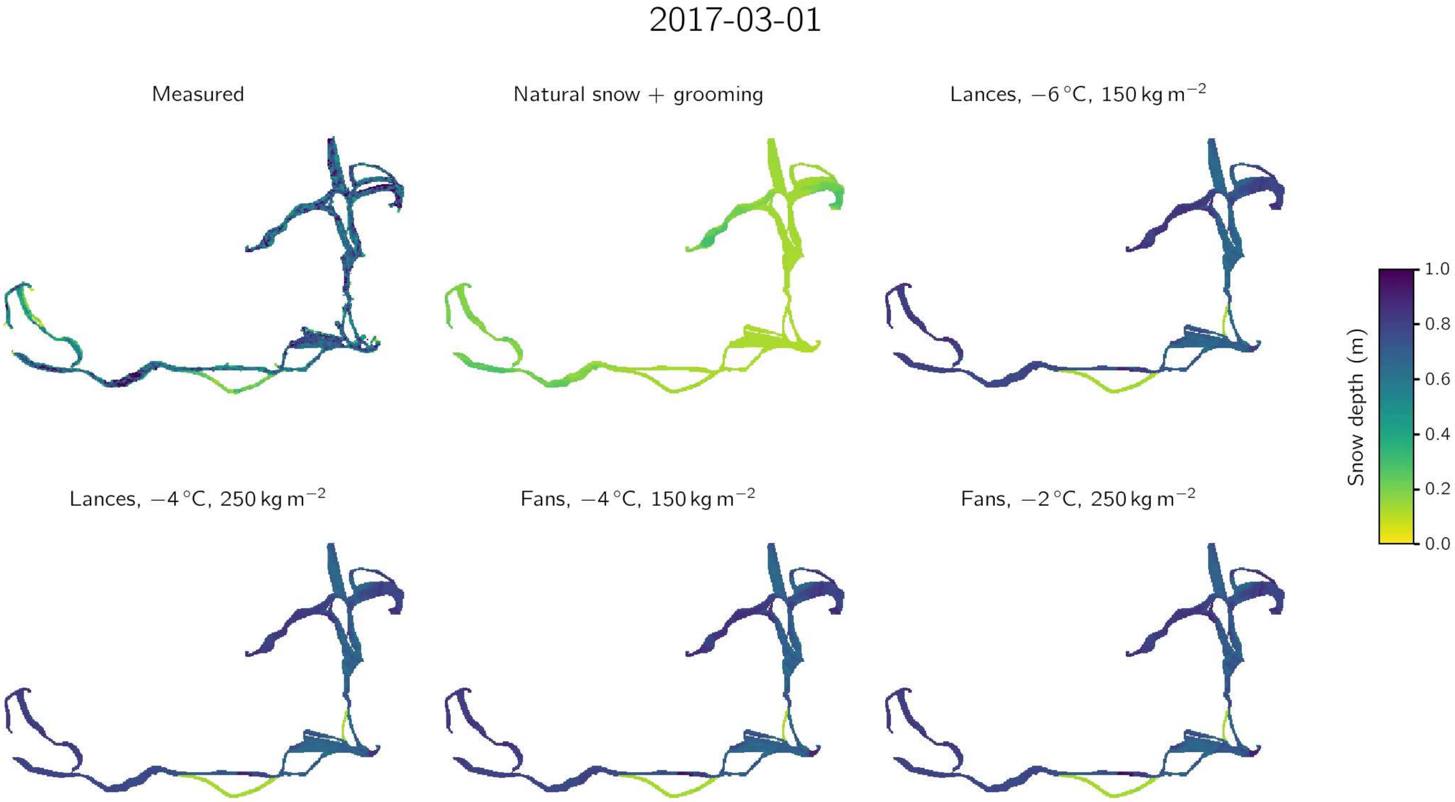
Results: snow depth





Results: snow depth





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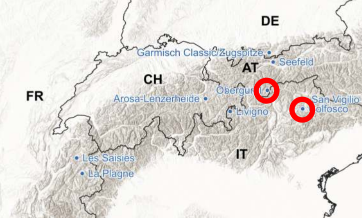
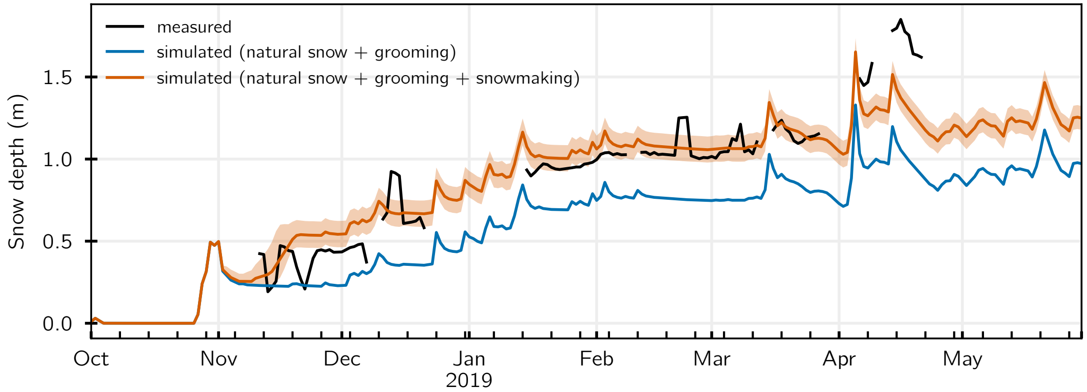
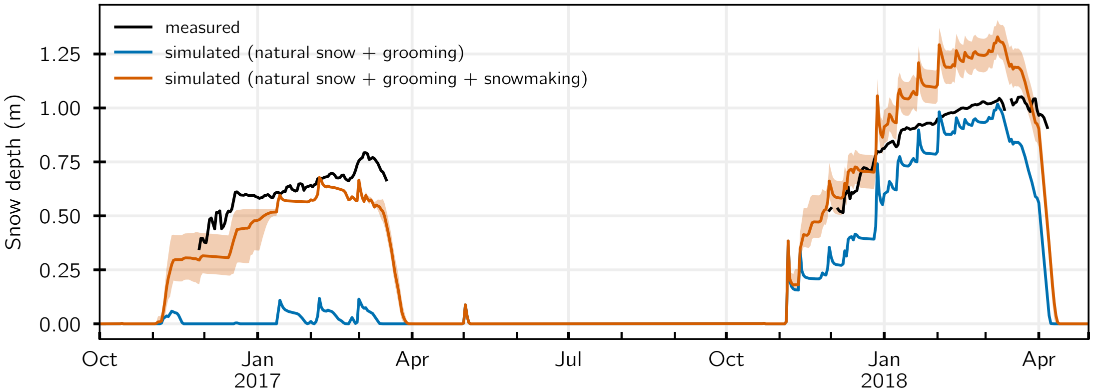
Results: snow depth (temporal evolution)



Obergurgl, 2770 m a.s.l.



Colfosco, 1660 m a.s.l.



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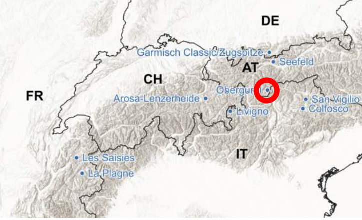
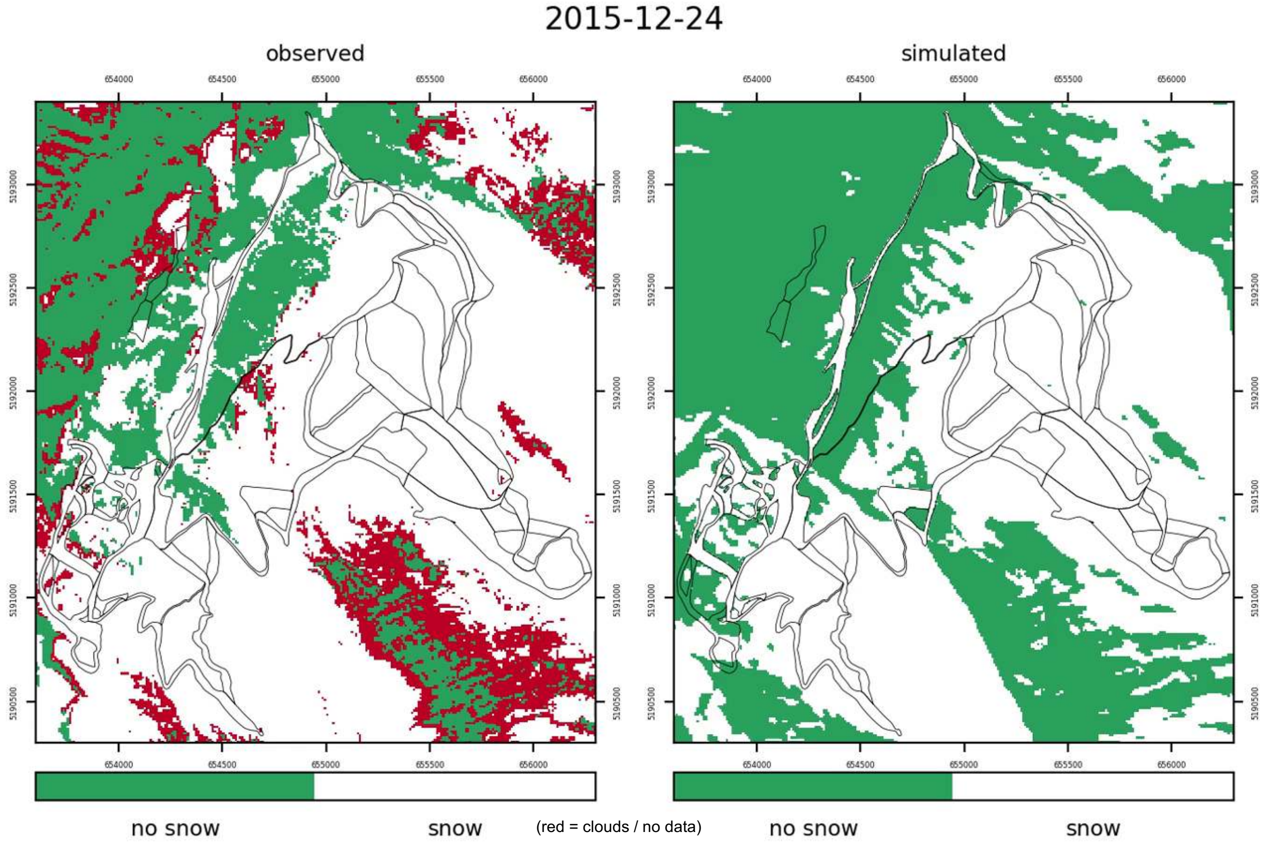
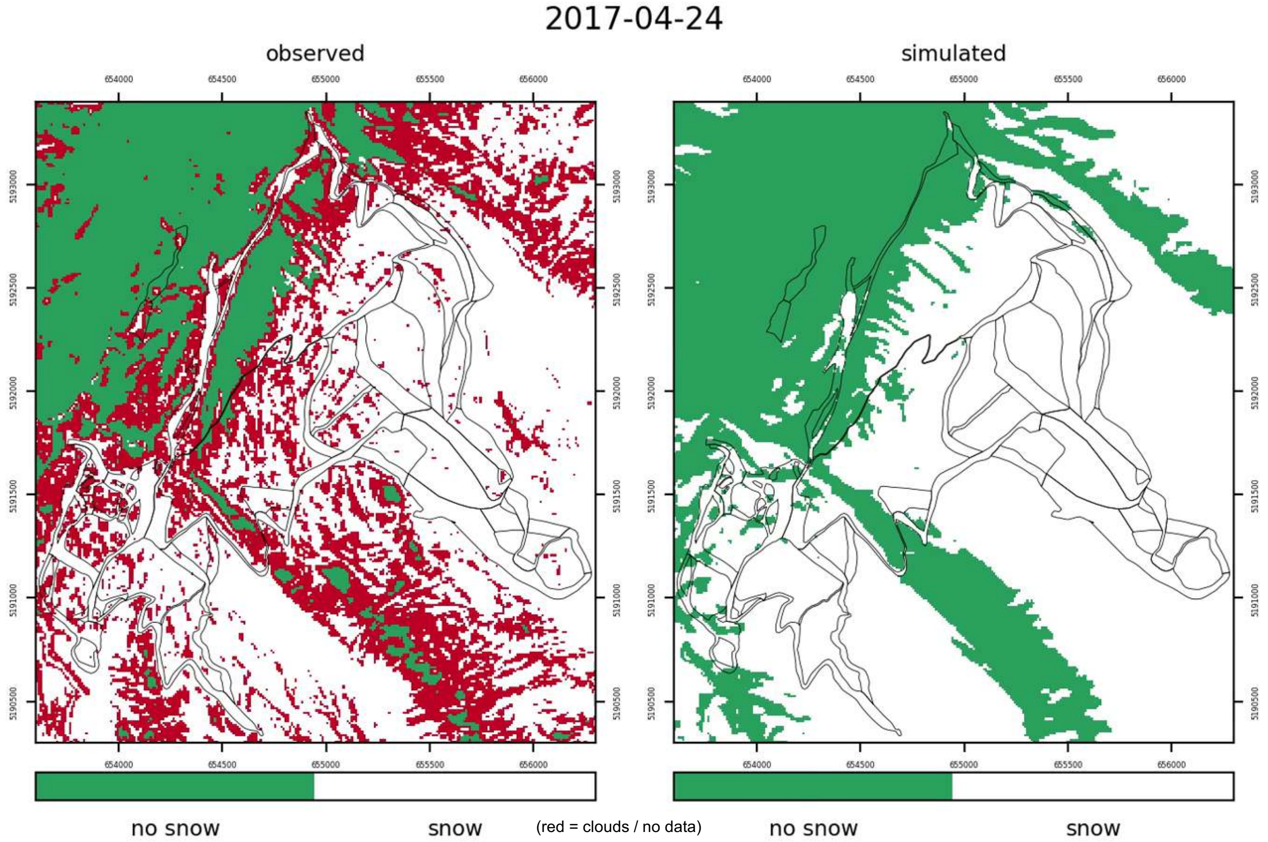
Results: snow cover maps

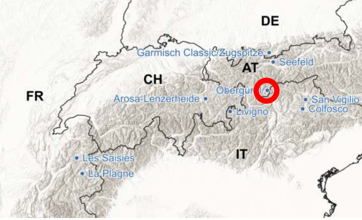


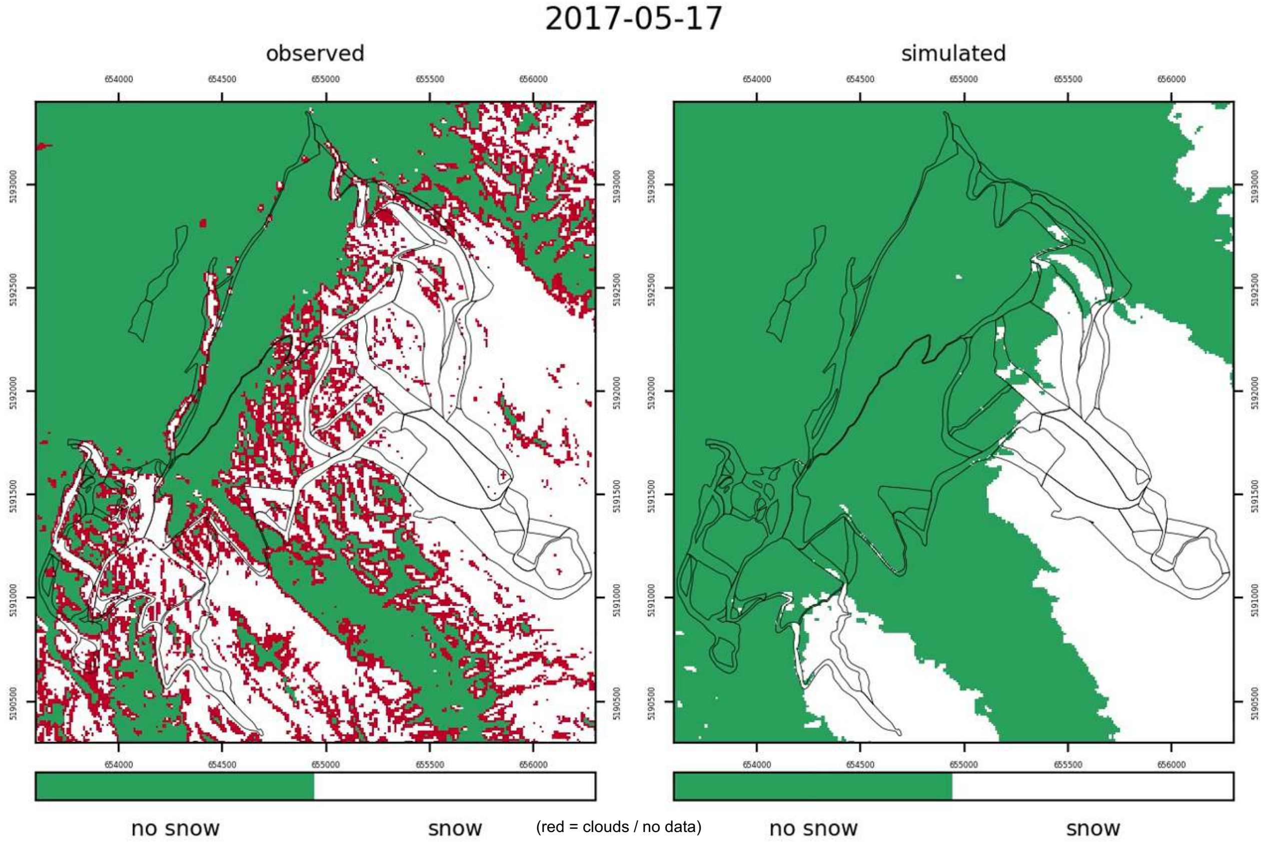


Results: snow cover maps



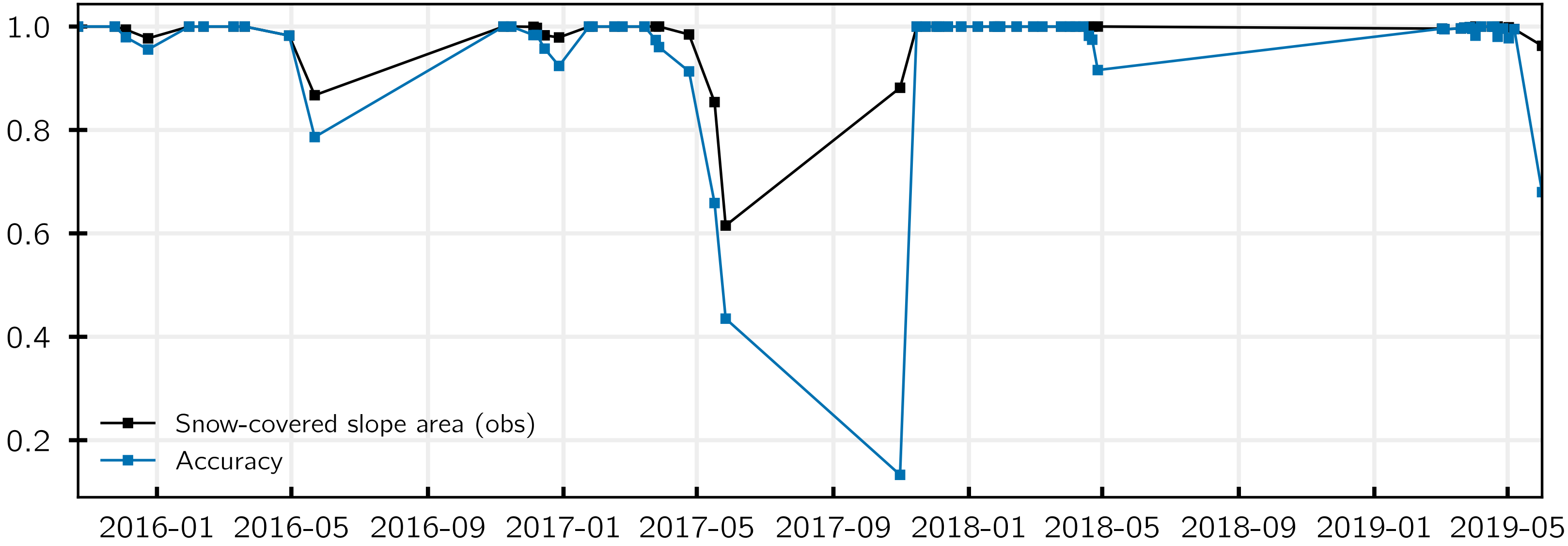
Results: snow cover maps





Results: snow cover maps

Evaluation for slope pixels only



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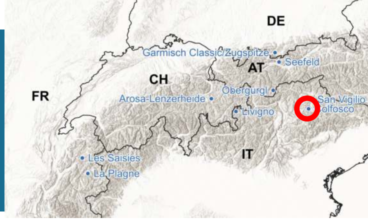
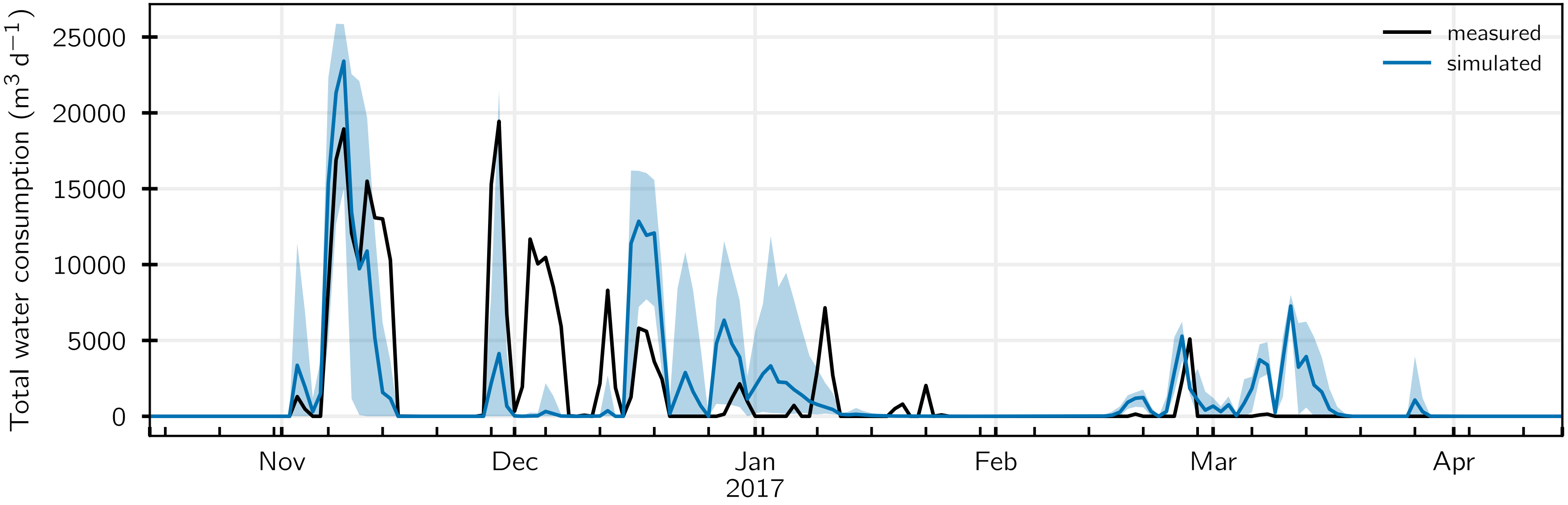
Results: water consumption





(blue shading = range of snow management configurations; solid line = mean)

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Conclusions

- Model implementation represents state of the art of the integration of snow management processes in physically based snowpack models
- “Generic” snow management configurations produce robust results for all considered ski resorts even without further tuning
- Operational applications require assimilation of local measurements (snow depth and water consumption)

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Thank you!

Further information:

www.prosnow.org

Hanzer, F., Carmagnola, C. M., Ebner, P. P., Koch, F., Monti, F., Bavay, M., Bernhardt, M., Lafaysse, M., Lehning, M., Strasser, U., François, H., Morin, S.: Simulation of snow management in Alpine ski resorts using three different snow models. Cold Regions Science and Technology, 172, 102995. https://doi.org/10.1016/j.coldregions.2020.102995.

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