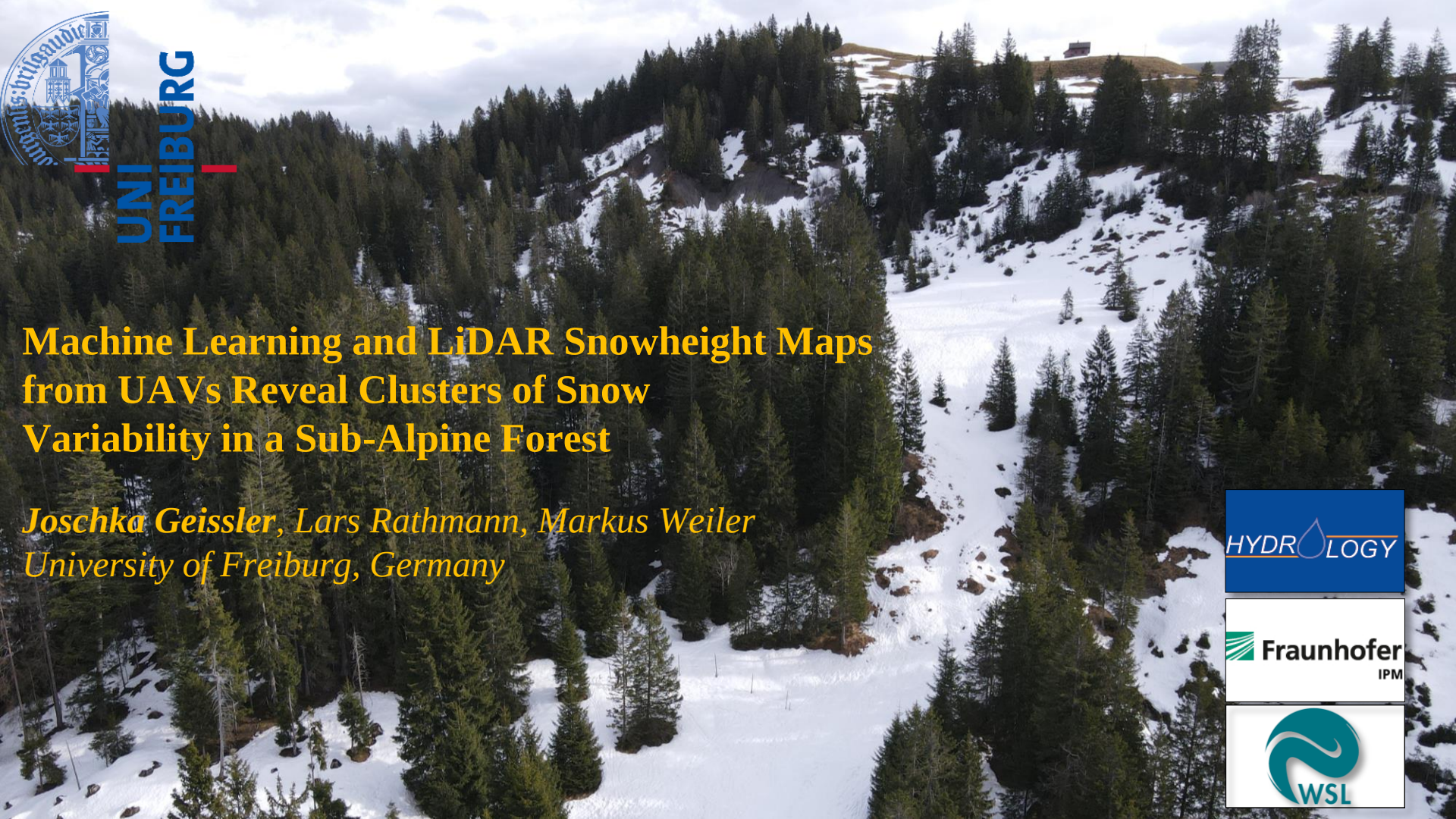
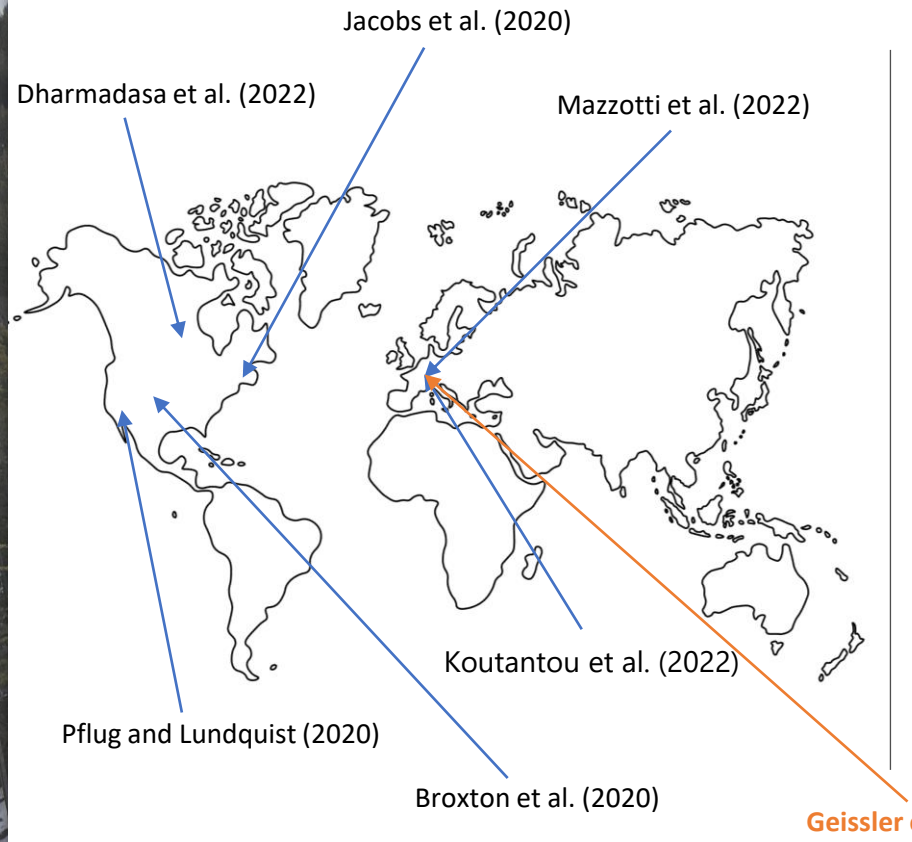
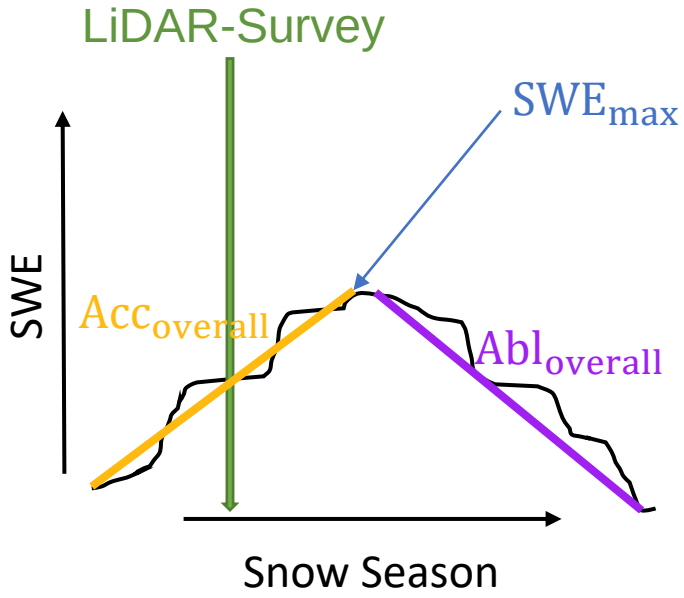
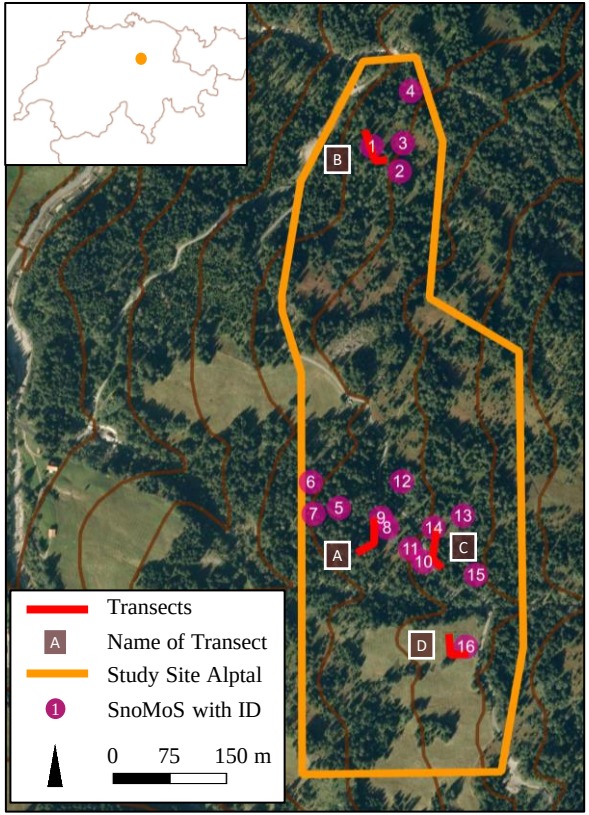


Machine Learning and LiDAR Snowheight Maps from UAVs Reveal Clusters of Snow Variability in a Sub-Alpine Forest

Joschka Geissler, *Lars Rathmann, Markus Weiler*
University of Freiburg, Germany


Jacobs et al. (2020)
Dharmadasa et al. (2022)
Mazzotti et al. (2022)
Koutantou et al. (2022)
Pflug and Lundquist (2020)
Broxton et al. (2020)
Geissler et al. (2023)


LiDAR-Survey
SWE$_{max}$
SWE
Acc$_{overall}$
Abl$_{overall}$
Snow Season



Study Site

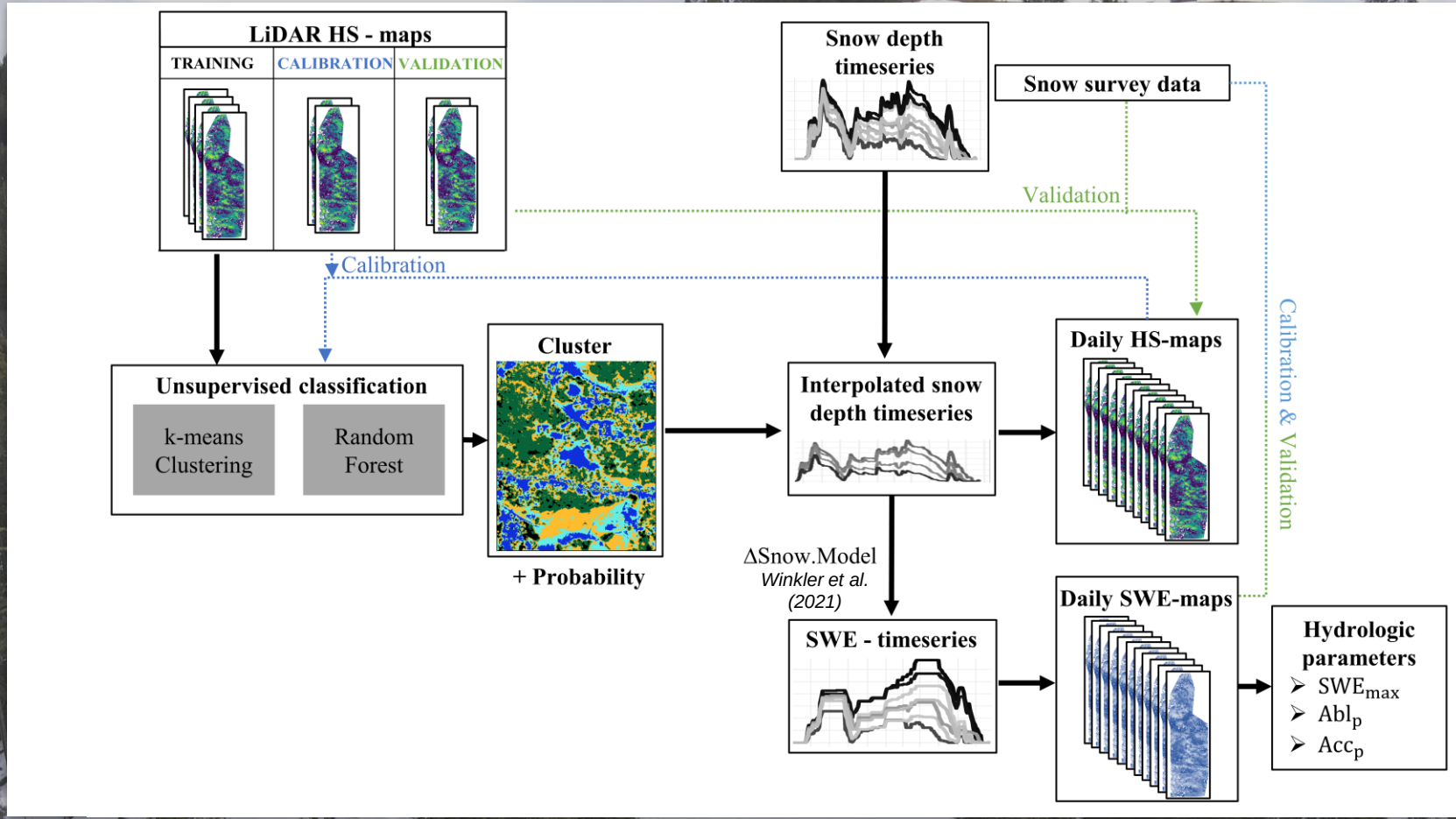
- 0.22 km²
- Minor influence of topography: West-facing hillside at 1200m (±35m)
- Heterogenous coniferous forest with heights of up to 35 m

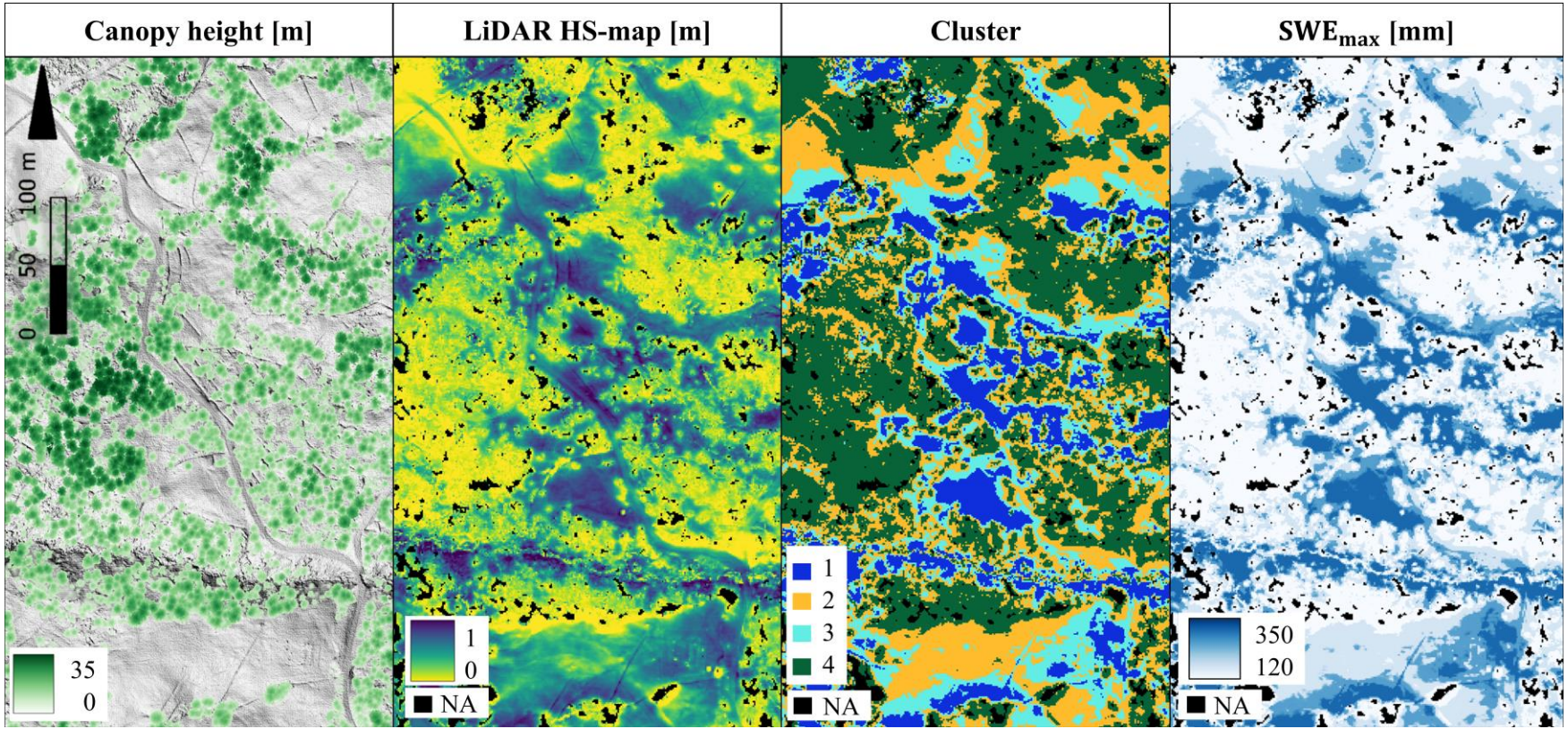
Data

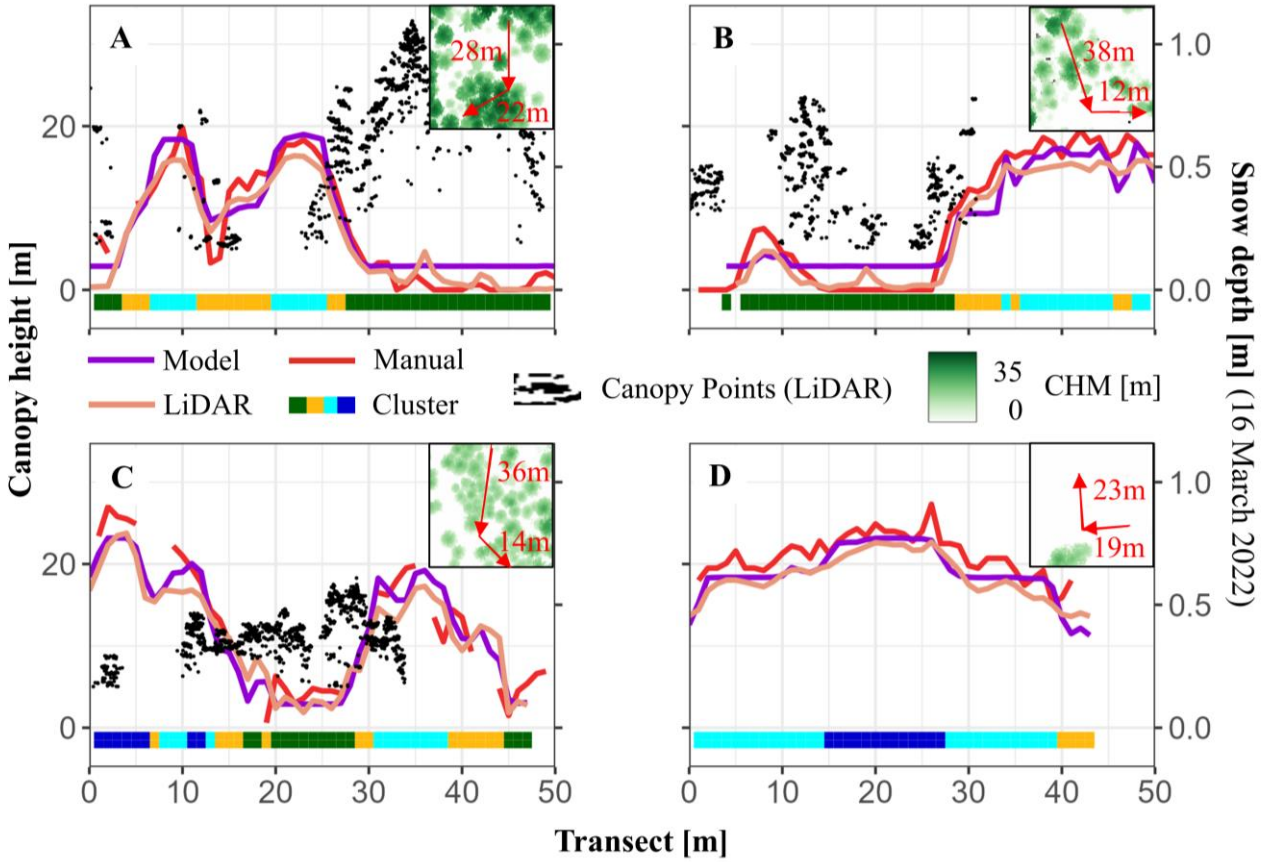
- 16 SnoMoS
- 8 UAV-based LiDAR Surveys (905 nm; Point density approx. 250 P/m²)
- 4 x 50 m transects x 9 manual Snow Surveys

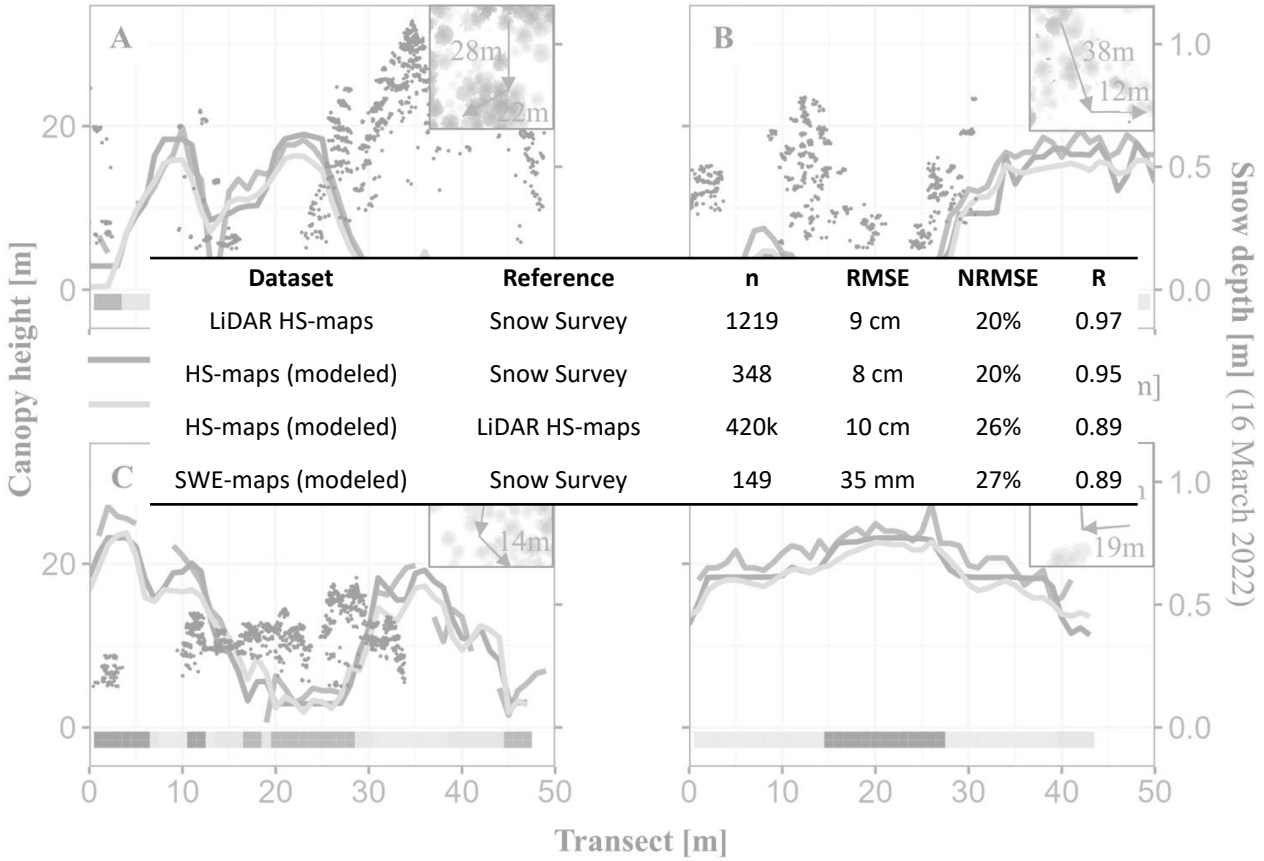




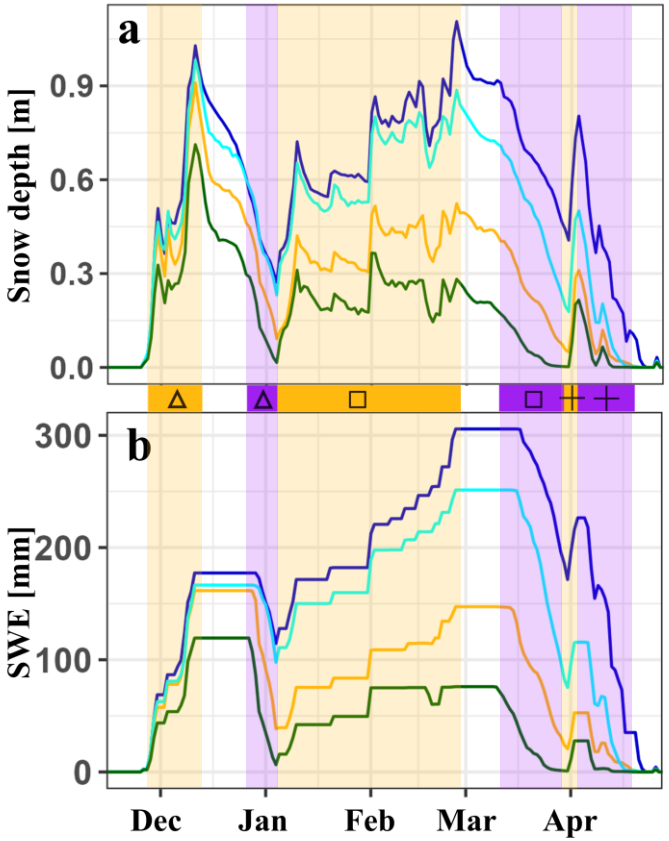

LiDAR HS - maps
TRAINING
CALIBRATION
VALIDATION
Snow depth timeseries
Snow survey data
Validation
Calibration
Unsupervised classification
k-means Clustering
Random Forest
Cluster
+ Probability
Interpolated snow depth timeseries
Daily HS-maps
Calibration & Validation
ΔSnow.Model
Winkler et al. (2021)
SWE - timeseries
Daily SWE-maps
Hydrologic parameters
SWEmax
Ablp
Accp

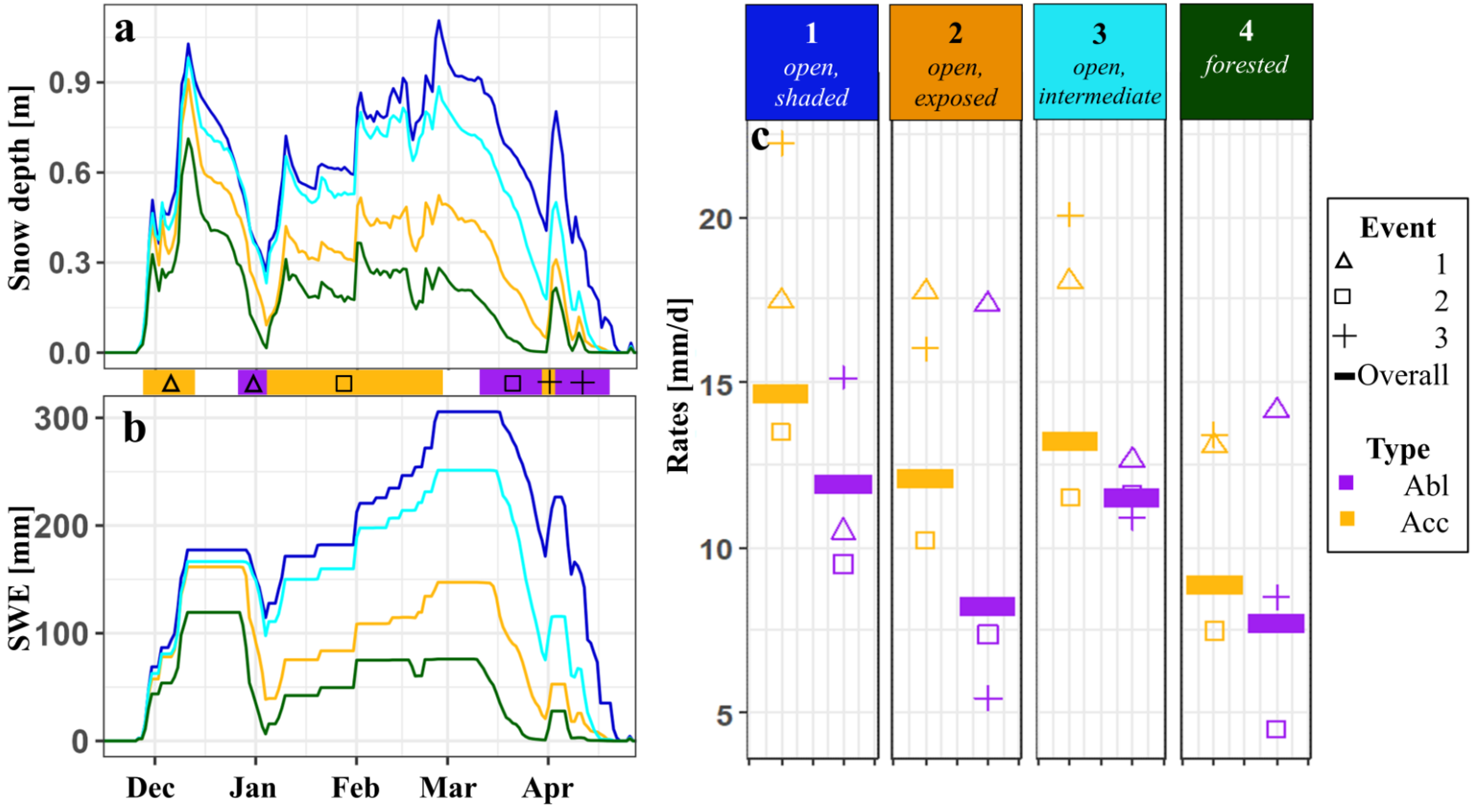

Canopy height [m]
LiDAR HS-map [m]
Cluster
SWE$_{max}$ [mm]
0
50
100 m
35
0
1
0
NA
1
2
3
4
NA
350
120
NA

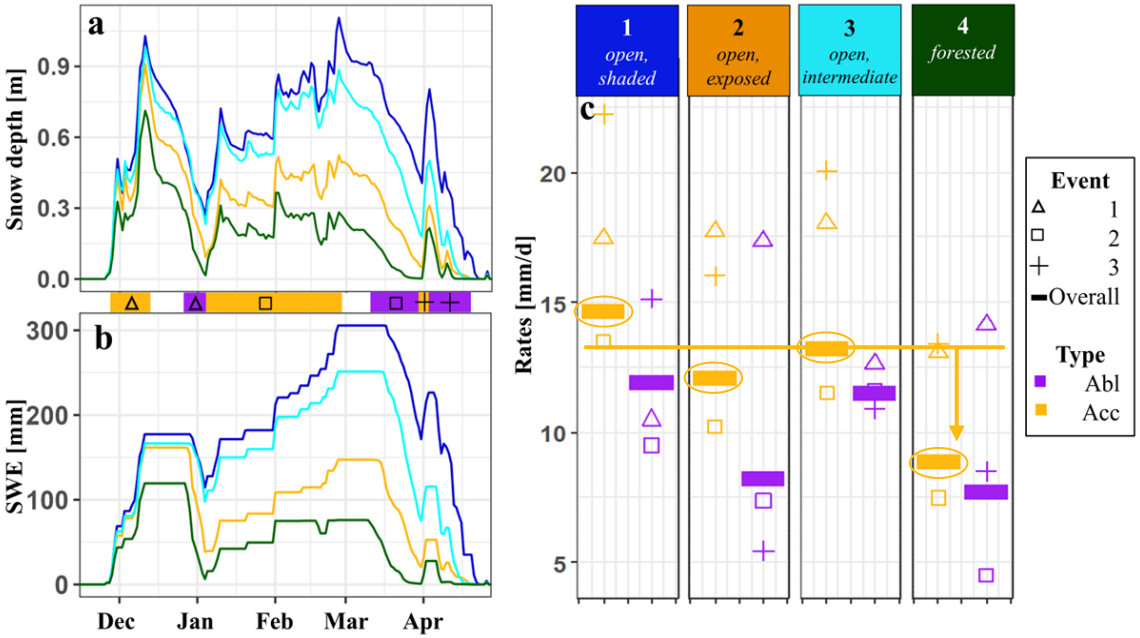

A
28m
22m
B
38m
12m
C
36m
14m
D
23m
19m
Canopy height [m]
Snow depth [m] (16 March 2022)
Transect [m]
Model
Manual
LiDAR
Cluster
Canopy Points (LiDAR)
35
0
CHM [m]



Dataset	Reference	n	RMSE	NRMSE	R
LiDAR HS-maps	Snow Survey	1219	9 cm	20%	0.97
HS-maps (modeled)	Snow Survey	348	8 cm	20%	0.95
HS-maps (modeled)	LiDAR HS-maps	420k	10 cm	26%	0.89
SWE-maps (modeled)	Snow Survey	149	35 mm	27%	0.89

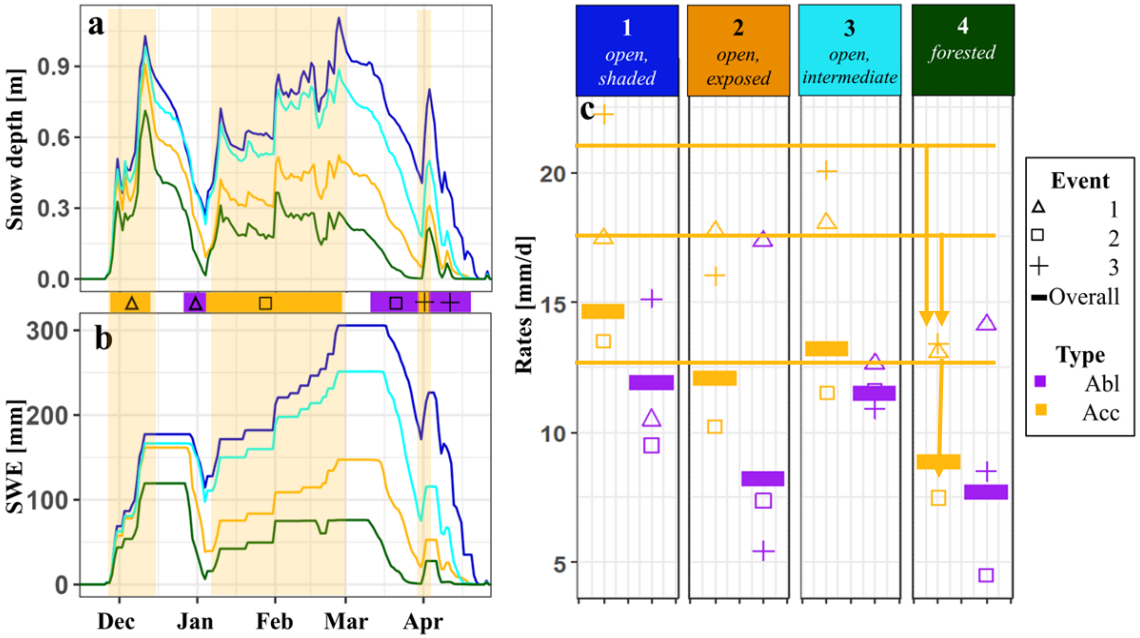

a
Snow depth [m]
0.9
0.6
0.3
0.0
b
SWE [mm]
300
200
100
0
Dec
Jan
Feb
Mar
Apr


a
Snow depth [m]
0.0
0.3
0.6
0.9
b
SWE [mm]
0
100
200
300
Dec
Jan
Feb
Mar
Apr
c
1
open, shaded
2
open, exposed
3
open, intermediate
4
forested
Rates [mm/d]
5
10
15
20
Event
1
2
3
Overall
Type
Abl
Acc



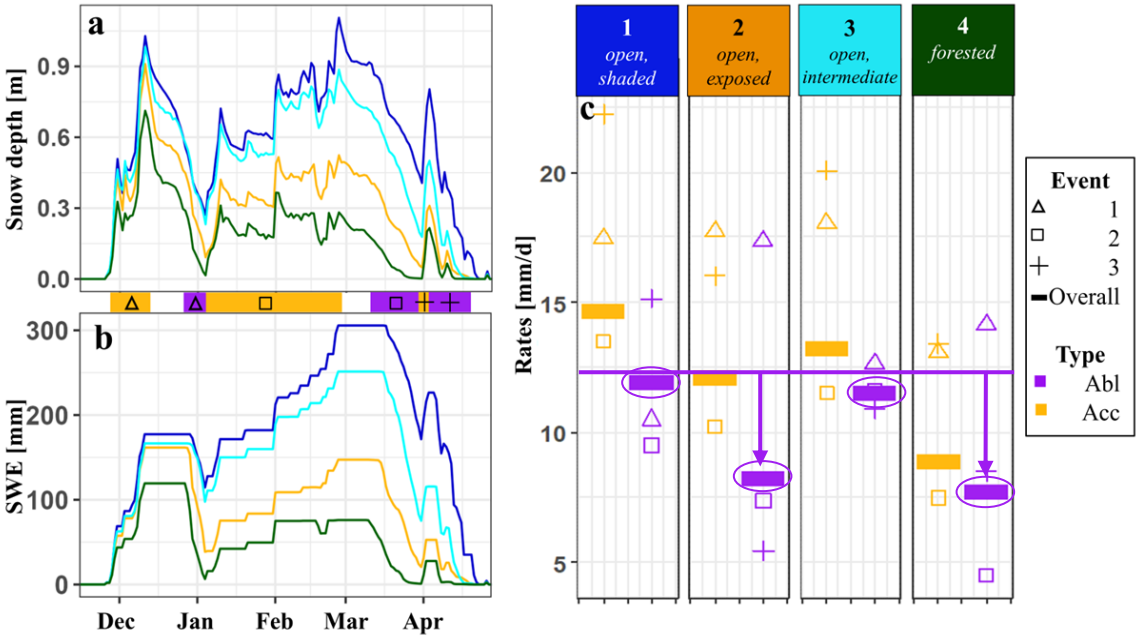
Accumulation

- Overall **accumulation reduced by 26% to 39%** from open to forested clusters.



Accumulation

- Overall **accumulation reduced by 26% to 39%** from open to forested clusters.
- High correlation between accumulation events (R: 0.81-0.83)

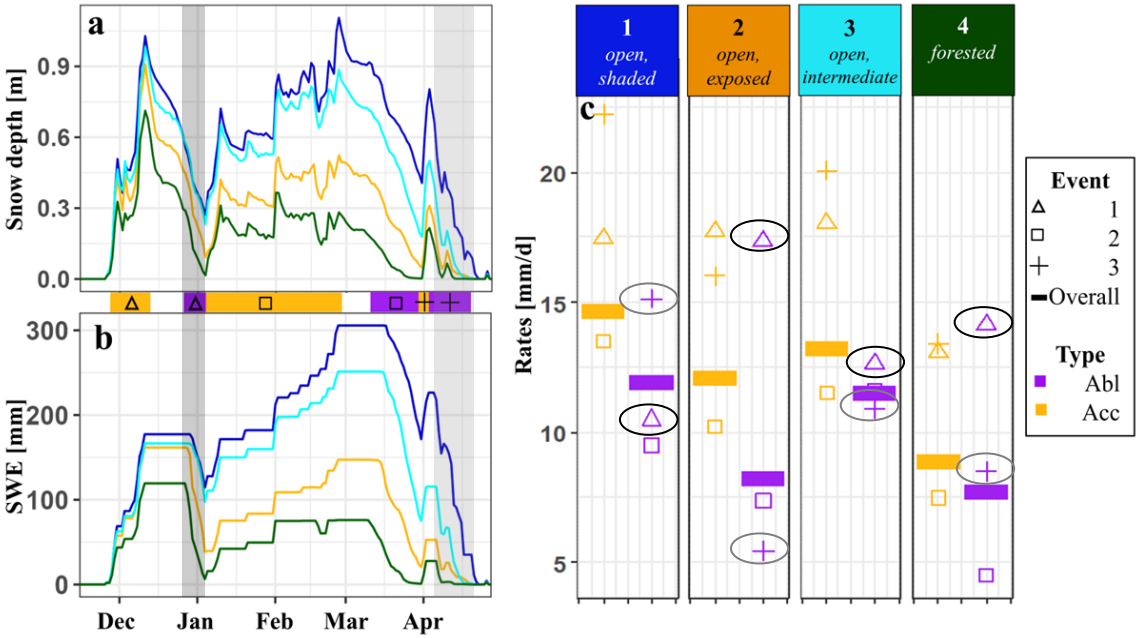


Accumulation

- Overall **accumulation reduced by 26% to 39%** from open to forested clusters.
- High correlation between accumulation events (R: 0.81-0.83)

Ablation

- Overall ablation rates are reduced in forested and open, exposed cluster by 28% - 36%

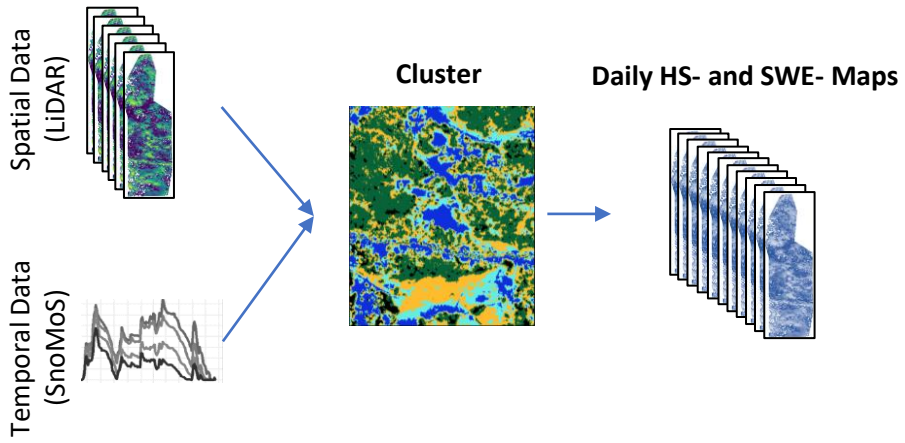


Accumulation

- Overall **accumulation reduced by 26% to 39%** from open to forested clusters.
- High correlation between accumulation events (R: 0.81-0.83)

Ablation

- Overall ablation rates are reduced in forested and open, exposed cluster by 28% - 36%
- Mid-winter and late-winter RoS show opposite relative ablation rates between the clusters (R:-0.91).



Conclusion

- Daily snow distribution (and hydrologic parameters) based on experimental data.
- Workflow transferable to other resolution, data and regions.

Outlook

- Validation of hyper-resolution snow models
- Are Clusters inter-annually consistent?
- Can Clusters help us to choose sensor locations and interpolate point-measurements?

Check my Publication for more:

- First LiDAR dataset that used a fixed-wing UAV to measure snow distribution
- Full, 3D co-registration of LiDAR point clouds using vegetation.

Literature

Broxton, P. D., Leeuwen, W. J., & Biederman, J. A. (2020). Forest cover and topography regulate the thin, ephemeral snowpacks of the semiarid Southwest United States. *Ecohydrology*, *13*(4). https://doi.org/10.1002/eco.2202

Dharmadasa, V., Kinnard, C., & Baraër, M. (2022). An Accuracy Assessment of Snow Depth Measurements in Agro-Forested Environments by UAV Lidar. *Remote Sensing*, *14*(7), 1649. https://doi.org/10.3390/rs14071649

Geissler J., Rathmann L, Weiler M. Spatio-temporal Snow Variability in a Sub-Alpine Forest predicted by Machine Learning and UAV-based LiDAR Snow Depth Maps. *ESS Open Archive* . January 24, 2023. https://doi.org/10.22541/essoar.167458059.97519903/v1

Jacobs J., Hunsaker A., Sullivan F, Palace M., & Cho E. (2020). *Shallow snow depth mapping with unmanned aerial systems lidar observations: A case study in Durham, New Hampshire, United States*. https://www.researchgate.net/publication/339338229_Shallow_snow_depth_mapping_with_unmanned_aerial_systems_lidar_observations_A_case_study_in_Durham_New_Hampshire_United_States https://doi.org/10.5194/tc-2020-37

Koutantou, K., Mazzotti, G., Brunner, P., Webster, C., & Jonas, T. (2022). Exploring snow distribution dynamics in steep forested slopes with UAV-borne LiDAR. *Cold Regions Science and Technology*, *200*(5), 103587. https://doi.org/10.1016/j.coldregions.2022.103587

Mazzotti, G., Currier, W. R., Deems, J. S., Pflug, J. M., Lundquist, J. D., & Jonas, T. (2019). Revisiting Snow Cover Variability and Canopy Structure Within Forest Stands: Insights From Airborne Lidar Data. *Water Resources Research*, *55*(7), 6198–6216. https://doi.org/10.1029/2019WR024898

Mazzotti, G., Webster, C., Quéno, L., Cluzet, B., & Jonas, T. (2022). Canopy structure, topography and weather are equally important drivers of small-scale snow cover dynamics in sub-alpine forests. *Hydrology and Earth System Sciences Discussions*, *2022*, 1–32. https://doi.org/10.5194/hess-2022-273

Pflug, J. M., & Lundquist, J. D. (2020). Inferring Distributed Snow Depth by Leveraging Snow Pattern Repeatability: Investigation Using 47 Lidar Observations in the Tuolumne Watershed, Sierra Nevada, California. *Water Resources Research*, *56*(9). https://doi.org/10.1029/2020WR027243

Winkler, M., Schellander, H., and Gruber, S.: Snow water equivalents exclusively from snow depths and their temporal changes: the Δsnow model, Hydrol. Earth Syst. Sci., 25, 1165–1187, https://doi.org/10.5194/hess-25-1165-2021, 2021.



Joschka Geissler
PhD student in Snowhydrology

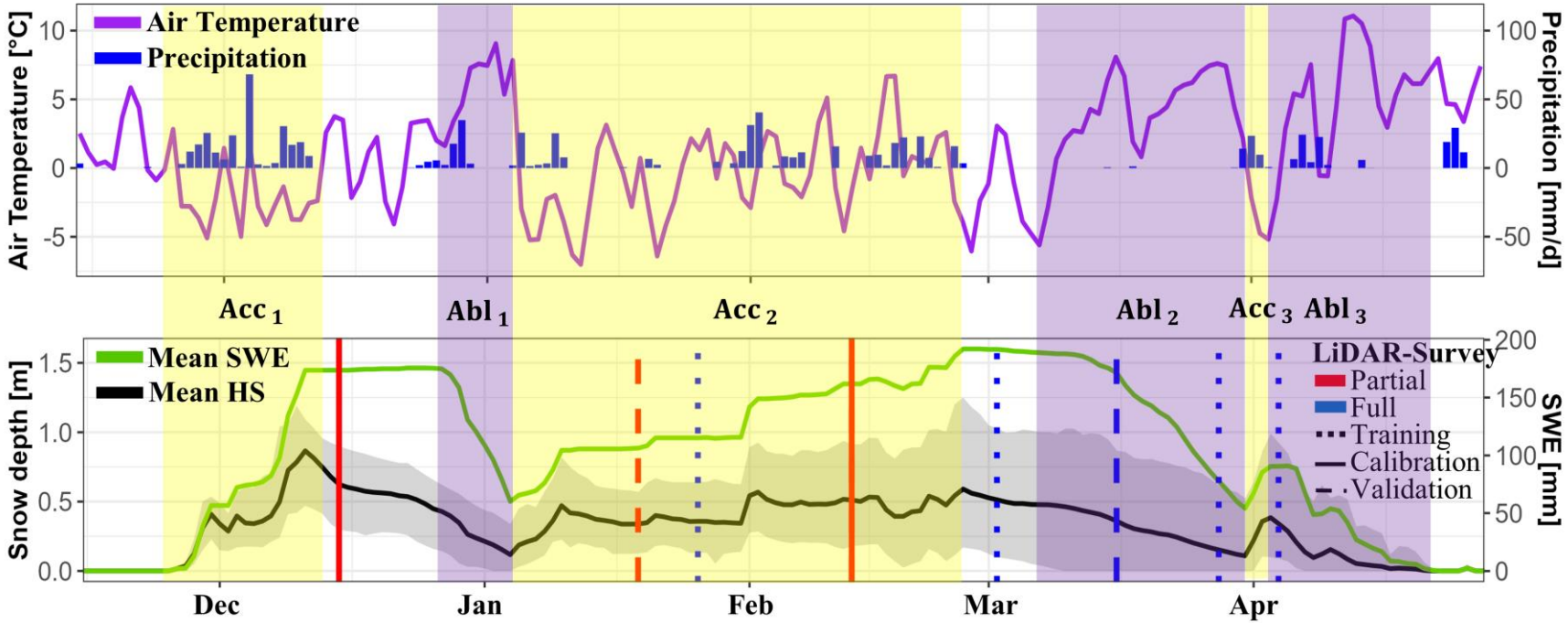
Professur für Hydrologie
Fakultät für Umwelt und Natürliche Ressourcen
Universität Freiburg
Friedrichstr. 39
D-79098 Freiburg

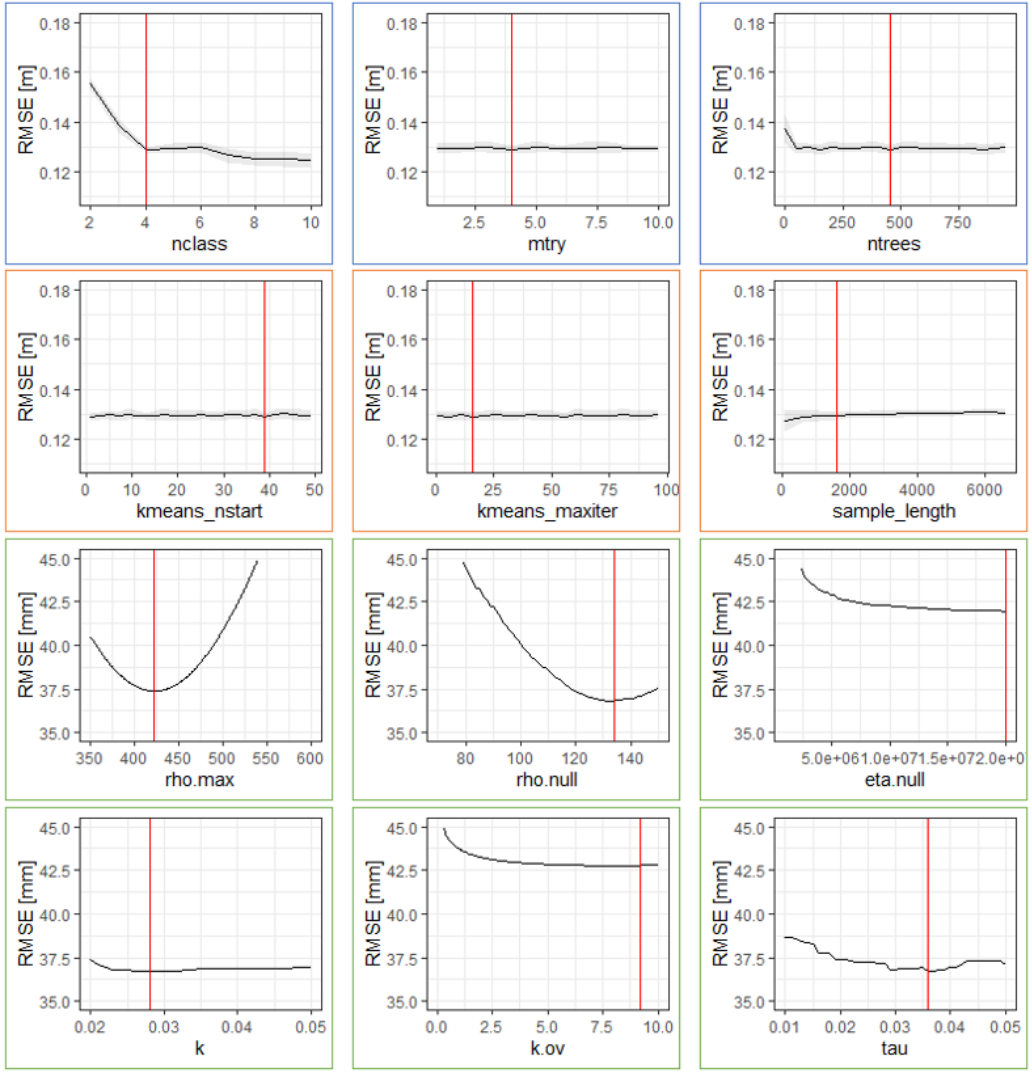
Phone: +49 761 - 203 3529
E-Mail: joschka.geissler@hydrology.uni-freiburg.de
Linked-in: https://www.linkedin.com/in/joschka-geissler-976113181/

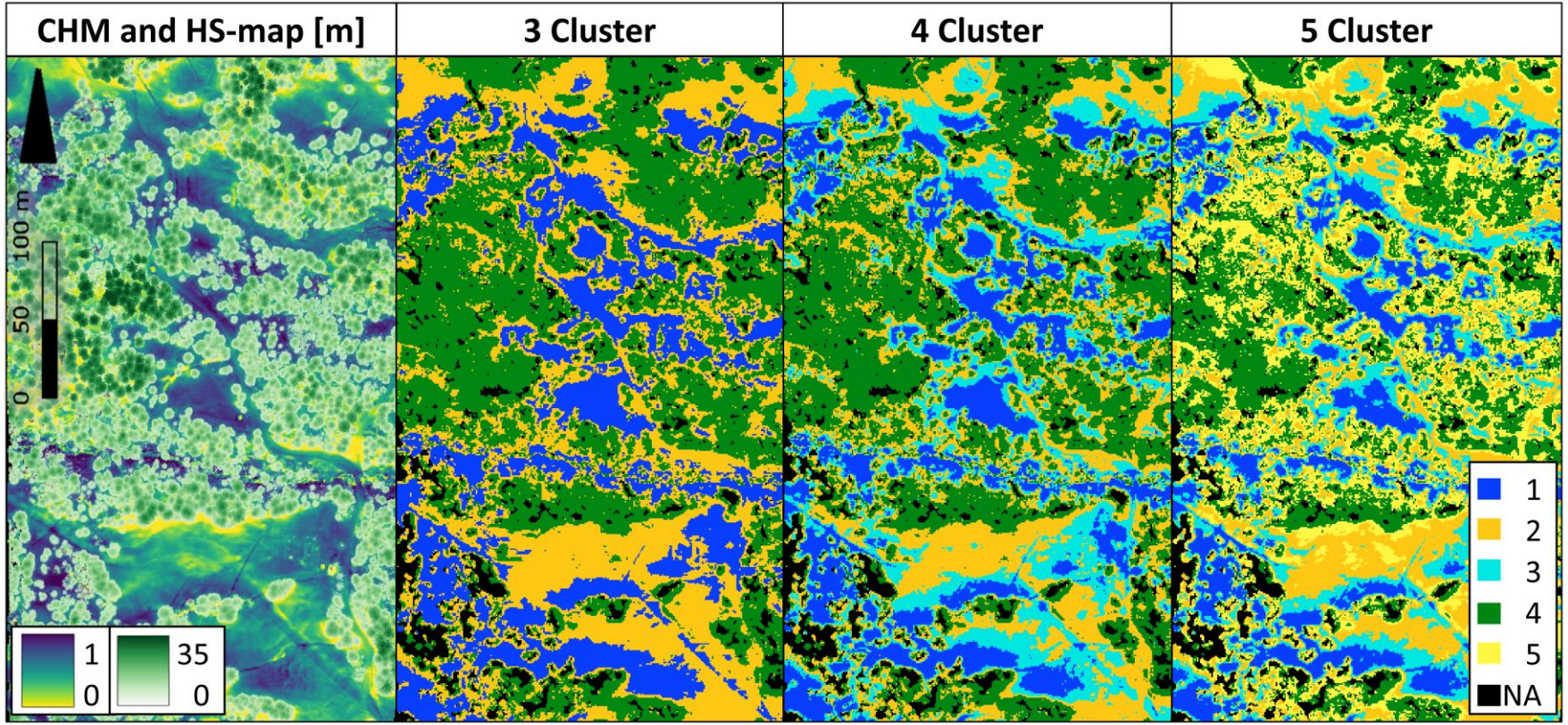


Calibration of Workflow Parameters

Application to Dataset: Alptal, Winter 2021/2022


Air Temperature
Precipitation
Air Temperature [°C]
Precipitation [mm/d]
Acc 1
Abl 1
Acc 2
Abl 2
Acc 3
Abl 3
Mean SWE
Mean HS
Snow depth [m]
SWE [mm]
LiDAR-Survey
Partial
Full
Training
Calibration
Validation
Dec
Jan
Feb
Mar
Apr


RMSE [m]
0.18
0.16
0.14
0.12
2 4 6 8 10
nclass
2.5 5.0 7.5 10.0
mtry
0 250 500 750
ntrees
0 10 20 30 40 50
kmeans_nstart
0 25 50 75 100
kmeans_maxiter
0 2000 4000 6000
sample_length
RMSE [mm]
45.0
42.5
40.0
37.5
35.0
350 400 450 500 550 600
rho.max
80 100 120 140
rho.null
5.0e+06 1.0e+07 1.5e+07 2.0e+0
eta.null
0.02 0.03 0.04 0.05
k
0.0 2.5 5.0 7.5 10.0
k.ov
0.01 0.02 0.03 0.04 0.05
tau


CHM and HS-map [m]
3 Cluster
4 Cluster
5 Cluster
0
50
100 m
1
0
35
0
1
2
3
4
5
NA



LiDAR Data

System, Data Pre-Processing and Co-Registration

LiDAR System

UAV:

DeltaQuad Pro VTOL Fixed Wing

Computer

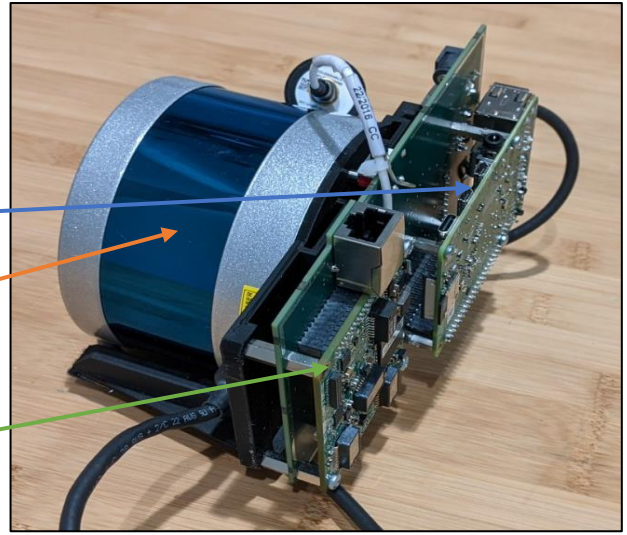
Raspberry Pi Zero WH v.1.1

LiDAR:

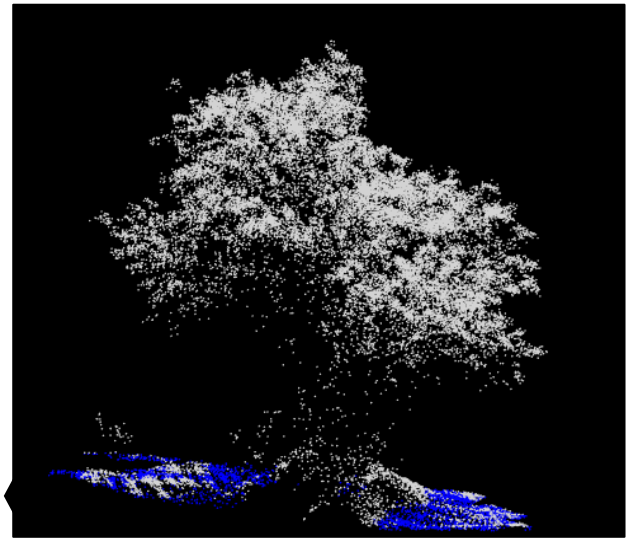
Velodyne Puck LITE
(Dual Return, 905 nm)

IMU

Applanix APX – 15
On-Board



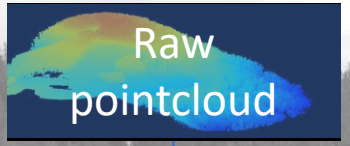




LiDAR Data and Mission:

- Altitude: 80 m above ground
- Flight speed: 19 m/s.
- 37 km in 33 minutes
- 40% Battery charge remaining
- Trajectory: 16 m distance between flightlines.
- Point density:
  - One Flight: 125 P/m²
  - Two merged flights: 250 P/m²





Pre-Processing

- Noise filtering — SOR
- Ground classification — CSF
- Error Assessment
  - *plane-fitting on roof*

Co-Registration

- Co-register Vegetation
- Apply transformation to full point cloud
- Error Assessment
  - *Roof*
  - *Reflectors*
  - *Reference points*

dDTM-Generation

- DTM generation — TIN
- dDTM = DTM_snow – DTM_nosnow

Co-Registration using snowfree areas

- Determine mean of snowfree areas
- Subtract from dDTM

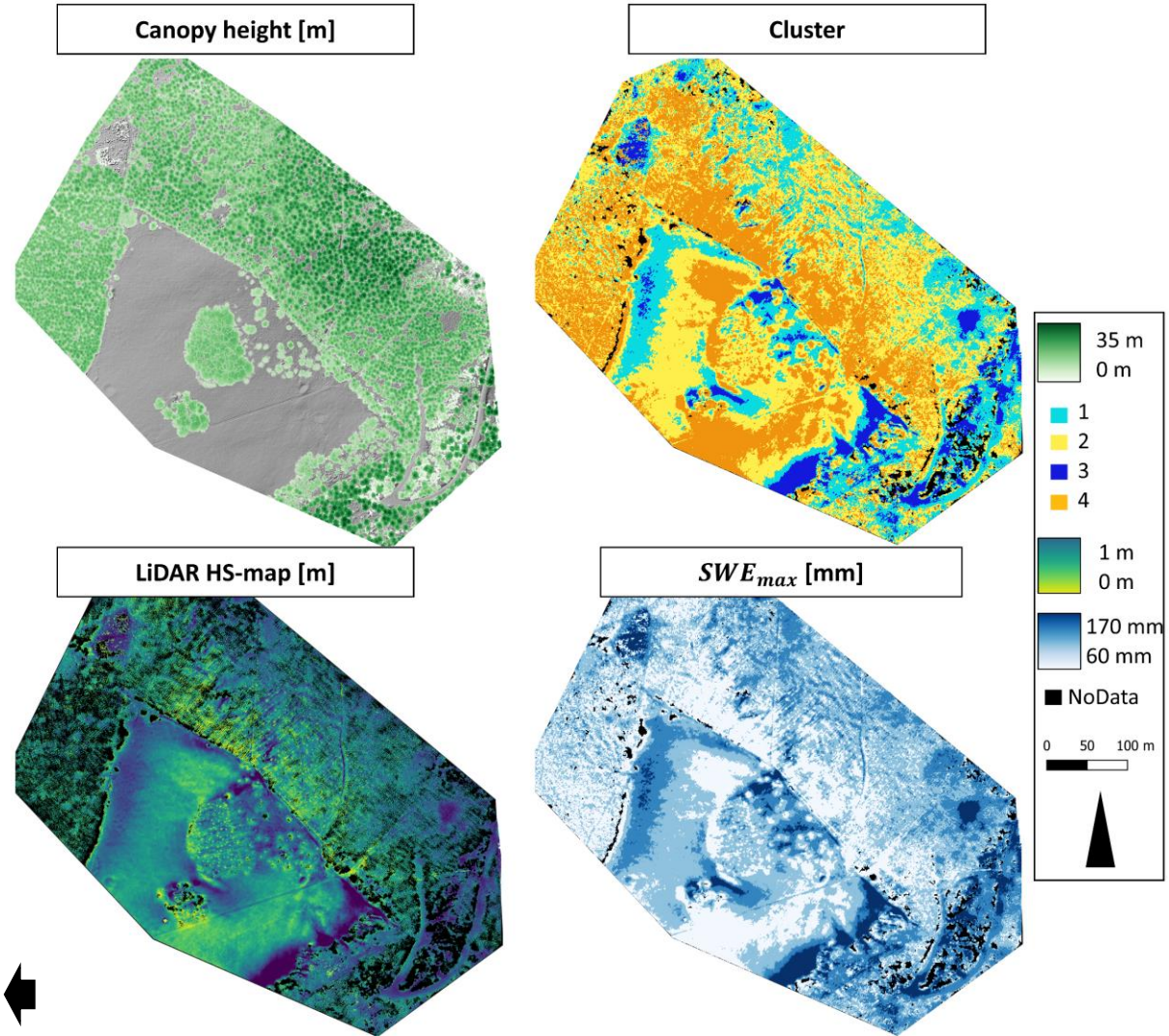


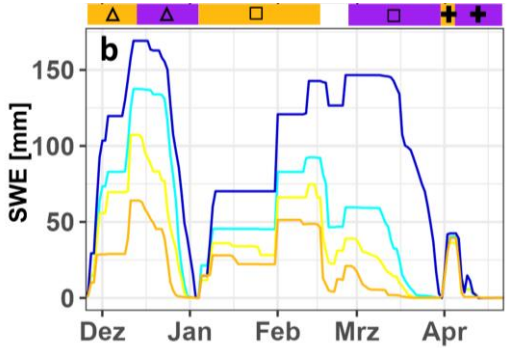
- Error Assessment
  - *Snowheight measurements*

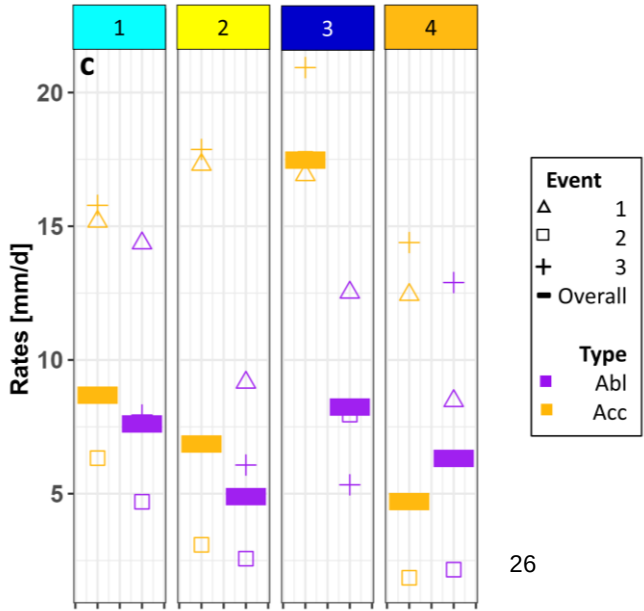


Transferability of Workflow

Application to Dataset: Schauinsland, Winter 2021/2022


Canopy height [m]
Cluster
LiDAR HS-map [m]
SWE_{max} [mm]
35 m
0 m
1
2
3
4
1 m
0 m
170 mm
60 mm
NoData
0 50 100 m


b
SWE [mm]
150
100
50
0
Dez
Jan
Feb
Mrz
Apr


1
2
3
4
c
Rates [mm/d]
20
15
10
5
Event
1
2
3
Overall
Type
Abl
Acc

Alptal 2021_2022

Dataset	Reference	n	NRMSE	NMEA	RMSE	MEA	R
LiDAR HS-maps	Snow Survey	1219	20%	16%	9 cm	7 cm	0.97
HS-maps (modeled)	Snow Survey	348	20%	15%	8 cm	6 cm	0.95
SWE-maps (modeled)	Snow Survey	149	26%	20%	35 mm	26 mm	0.89
HS-maps (modeled)	LiDAR HS-maps	420960	27%	23%	10 cm	7 cm	0.89

Schauinsland 2021_2022

Dataset	Reference	n	NRMSE	NMEA	RMSE	MEA	R
LiDAR HS-maps	Snow Survey	1163	28%	22%	7 cm	5 cm	0.91
HS-maps (modeled)	Snow Survey	461	36%	27%	9 cm	7 cm	0.82
SWE-maps (modeled)	Snow Survey	67	28%	22%	34 mm	30 mm	0.73
HS-maps (modeled)	LiDAR HS-maps	220908	36%	26%	9 cm	6 cm	0.84

Davos? /Sierra Nevada?



Inter-annual consistency of clusters

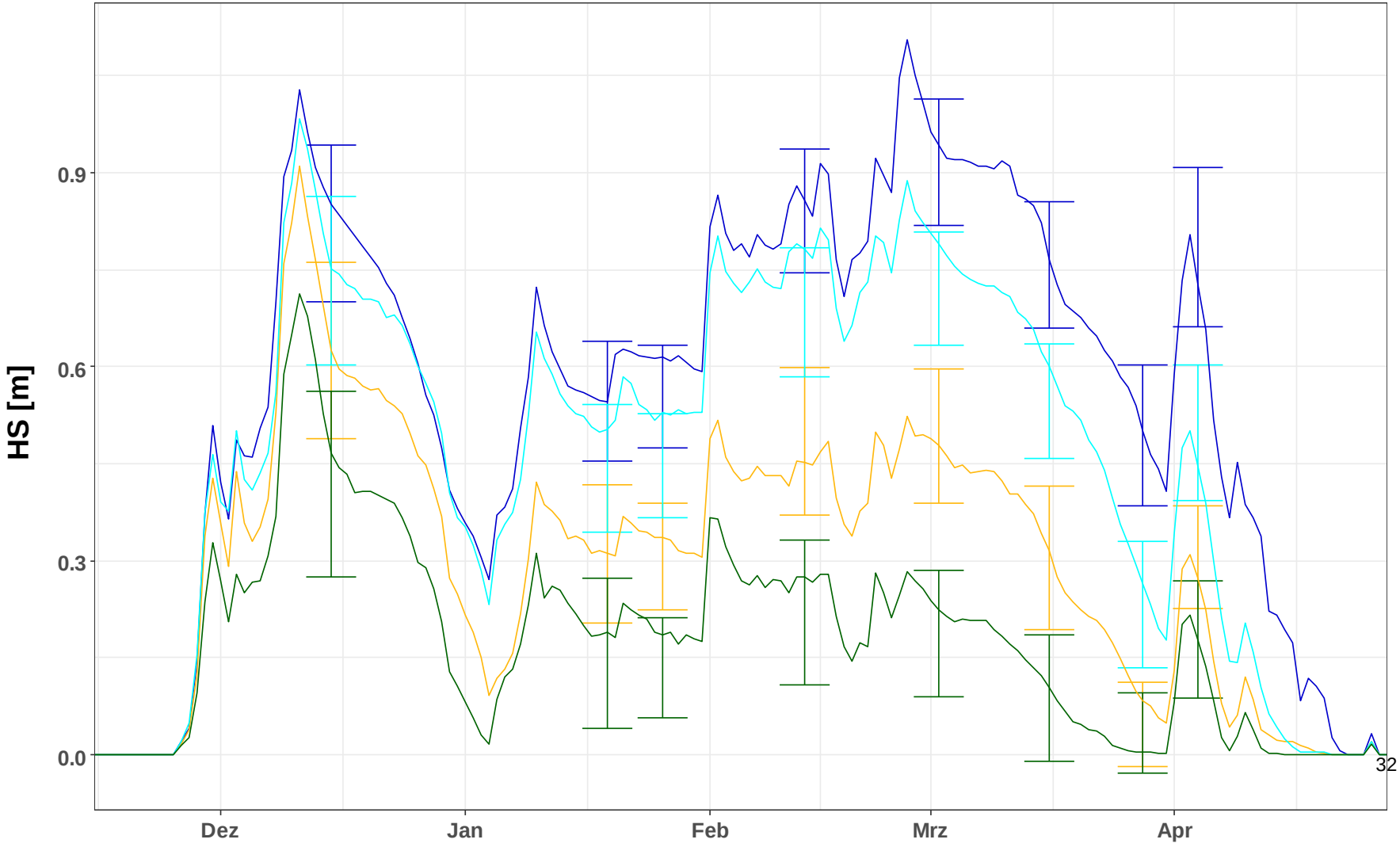
Comparison with Dataset: Alptal, Winter 2022/2023

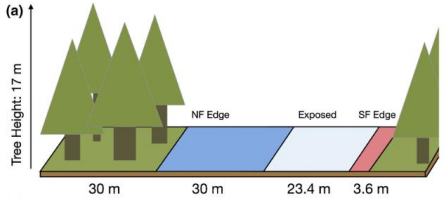
Inter-annual consistency of clusters



In-cluster Variability

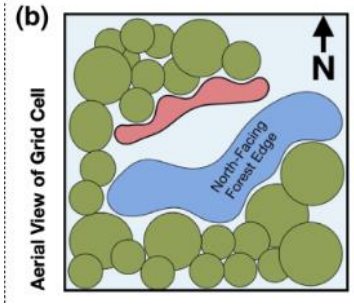
Dataset: Alptal, Winter 2022/2023


HS [m]
0.0
0.3
0.6
0.9
Dez
Jan
Feb
Mrz
Apr
32

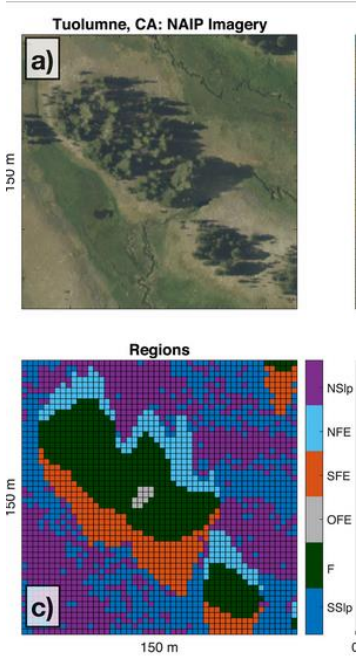


Model Implementation

Conceptual Diagram: Tiled Model Param.

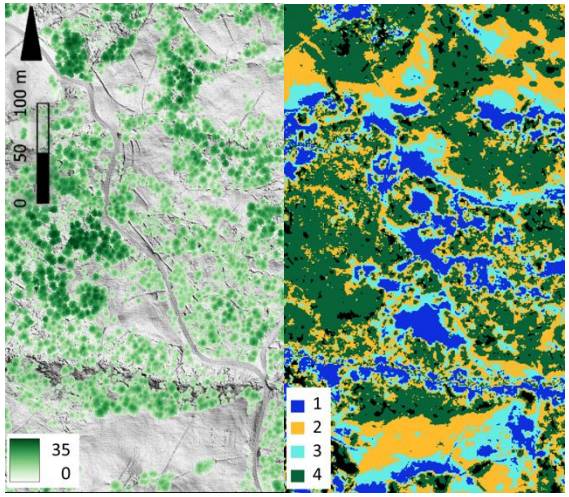


Currier et al. (2022)



Currier et al. (2018)

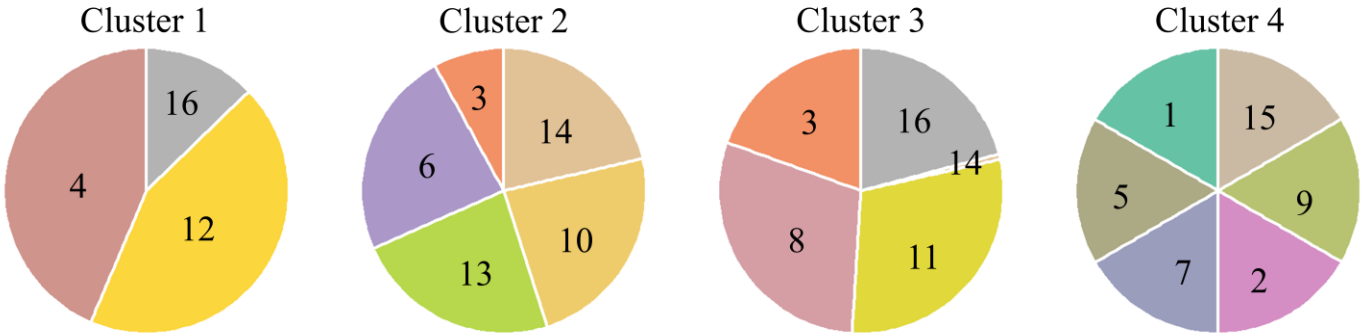
Konzeptueller Ansatz; Klassifikation basierend auf DSM und CHM; Musste für unterschiedliche Projektgebiete immer neu angesetzt werden.

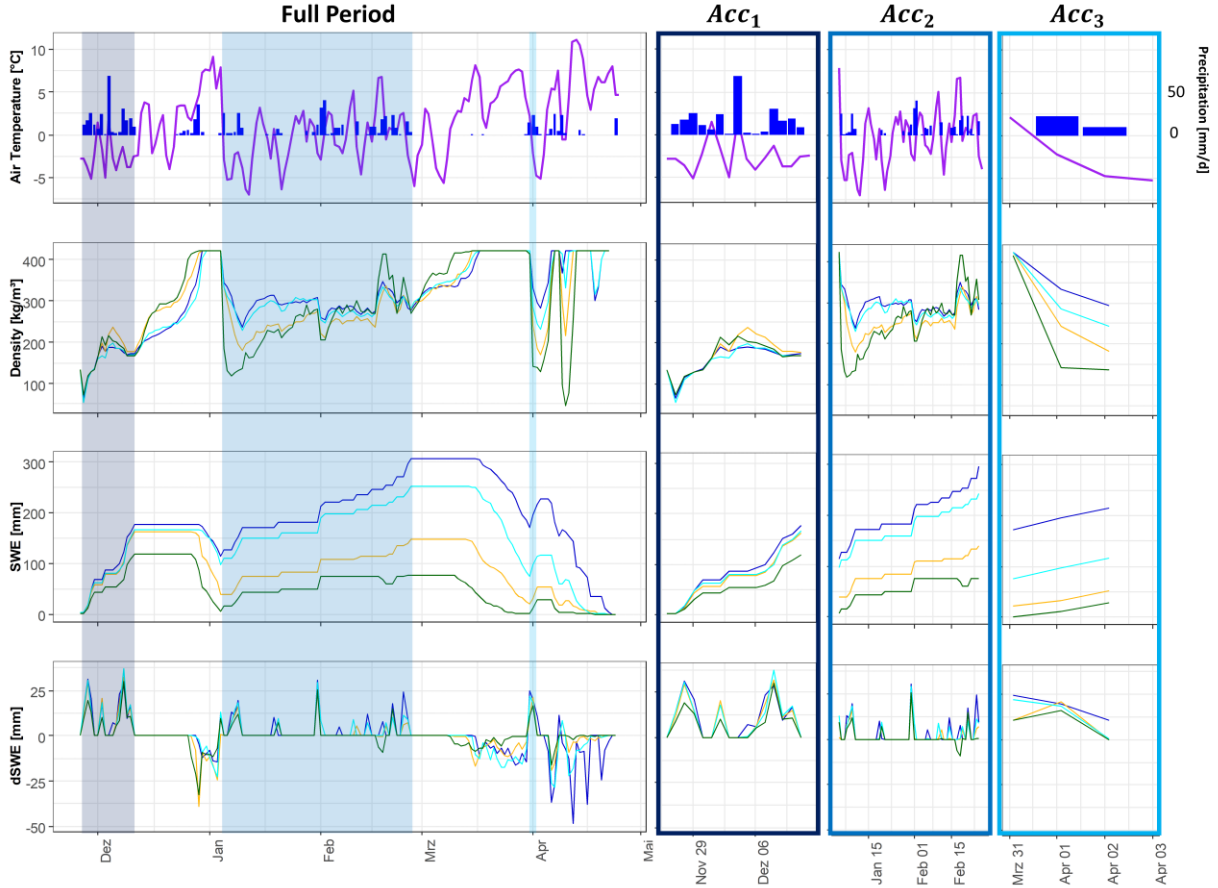


Cluster 2:

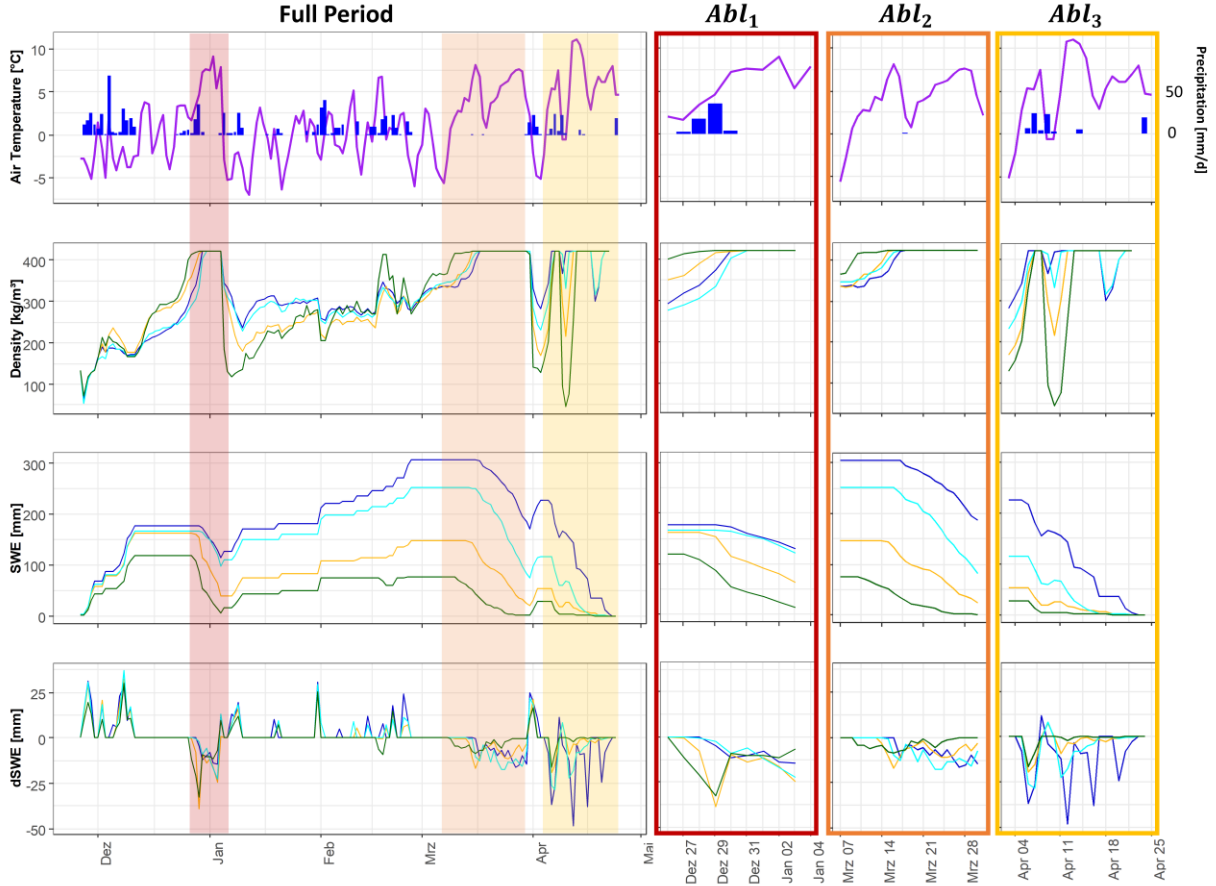
- Fasst kleine Vegetationslücken (D/H < 0.5) und exponierte Freiflächen zusammen.
- Bzgl. Akkumulation ergibt das Sinn.
- Bzgl. Ablation/Energiebilanzierung: Kann hier die emittierte LWR die Abschattung der SWR ausgleichen?

Dataset	Reference	n	NRMSE	NMEA	RMSE	MEA	R
LiDAR HS-maps	Snow Survey	1219	20%	16%	9 cm	7 cm	0.97
HS-maps (modeled)	Snow Survey	348	20%	15%	8 cm	6 cm	0.95
HS-maps (modeled)	LiDAR HS-maps	420960	27%	23%	10 cm	7 cm	0.89
SWE-maps (modeled)	Snow Survey	149	26%	20%	35 mm	26 mm	0.89

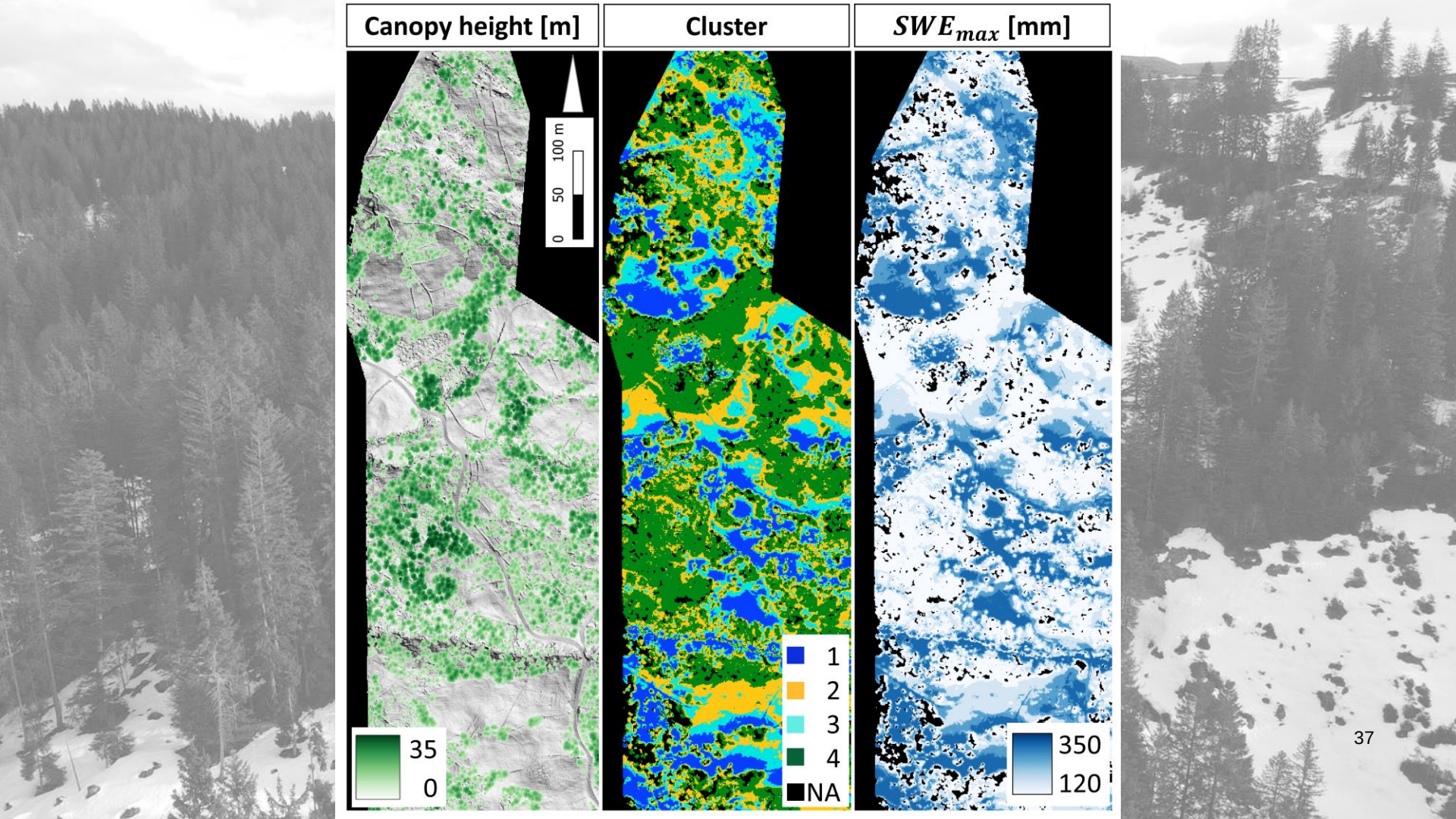


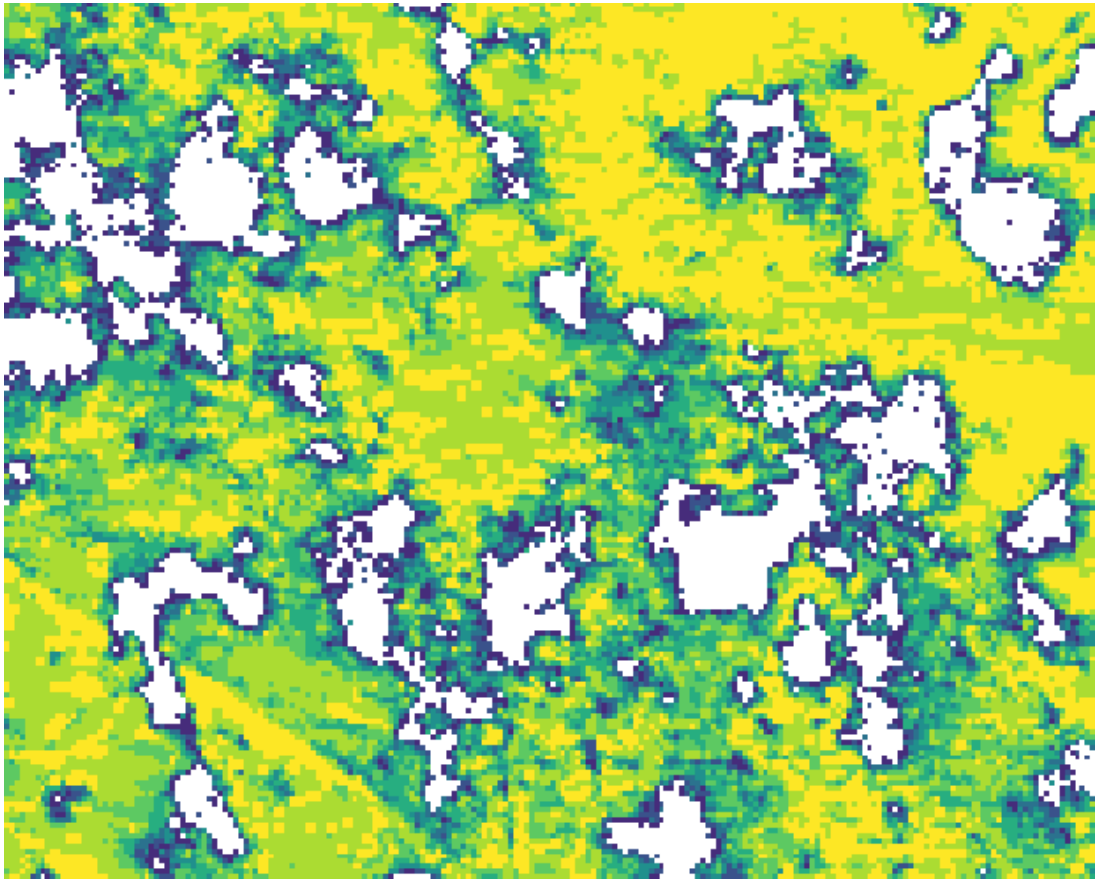


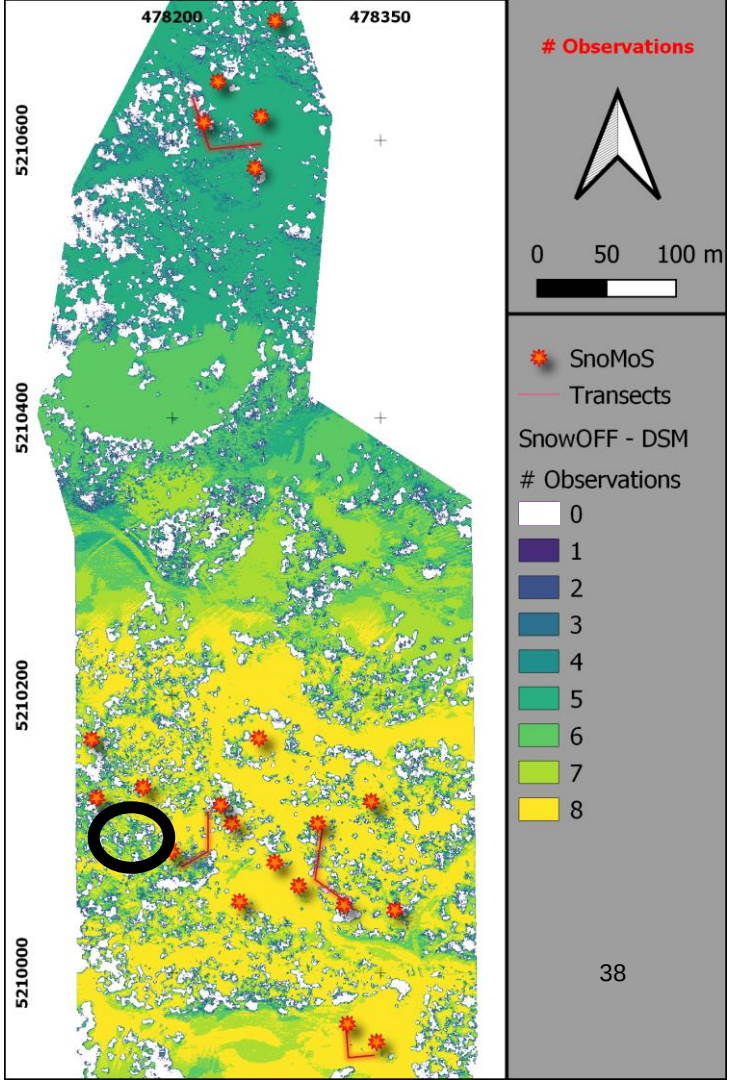
Cluster	Denotation	Color
1	Open, shaded	Blue
2	Open, exposed	Orange
3	Open, intermediate	Cyan
4	forested	Green

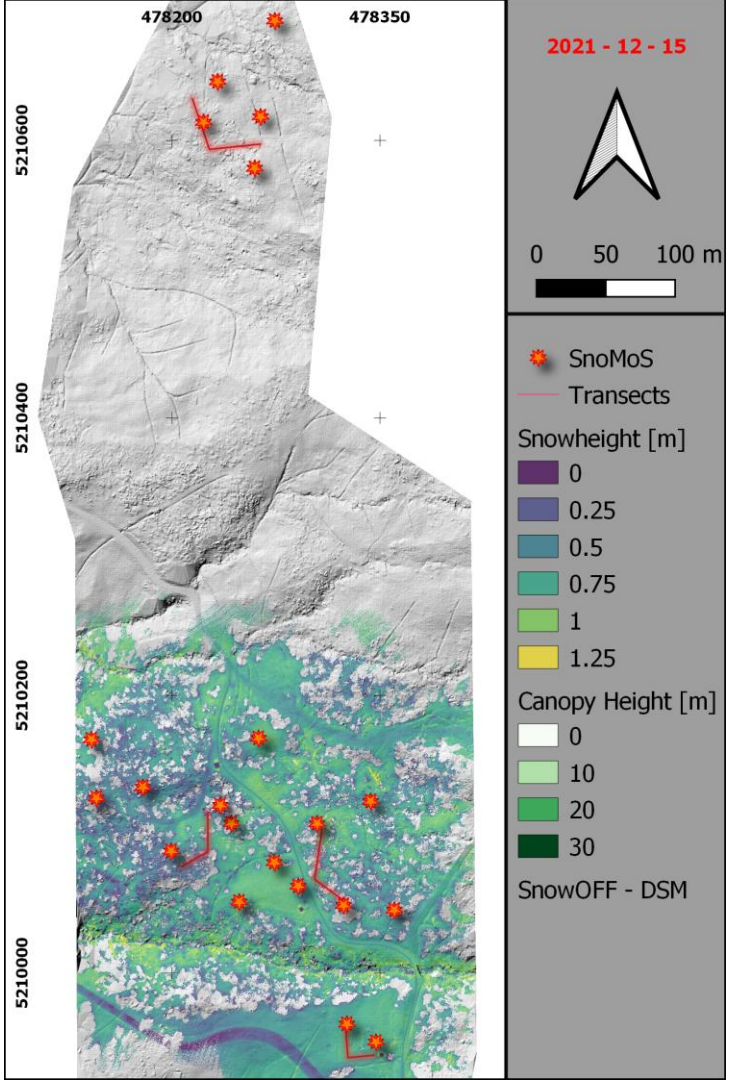


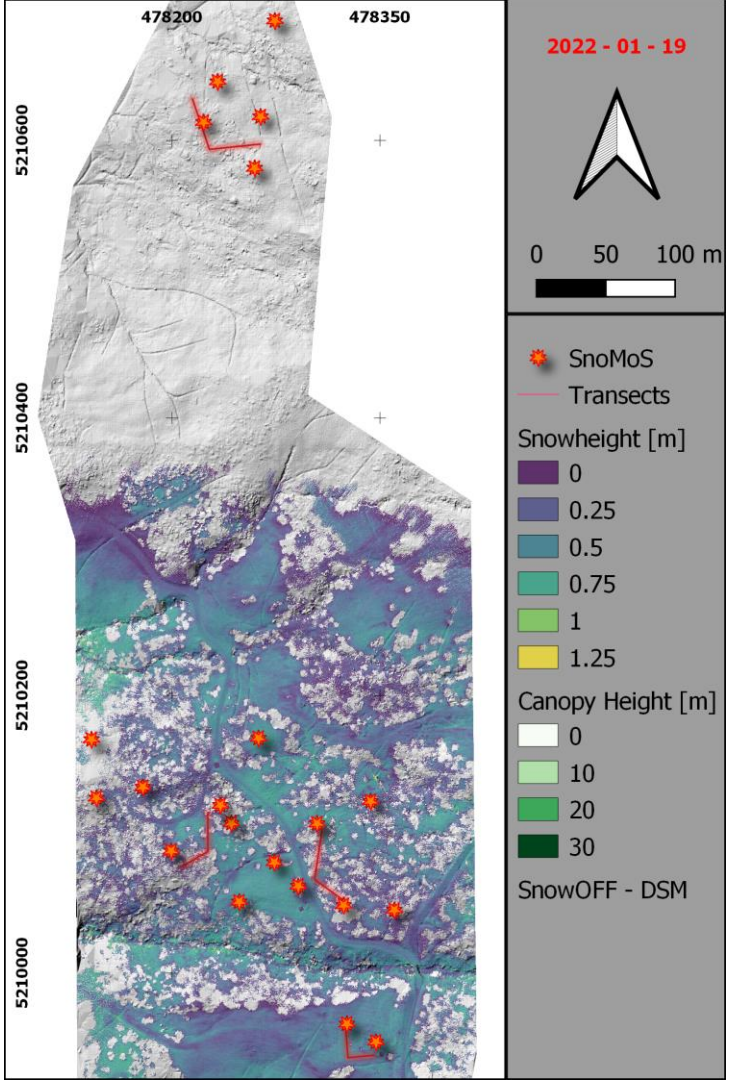
Cluster	Denotation	Color
1	Open, shaded	Blue
2	Open, exposed	Orange
3	Open, intermediate	Cyan
4	forested	Green

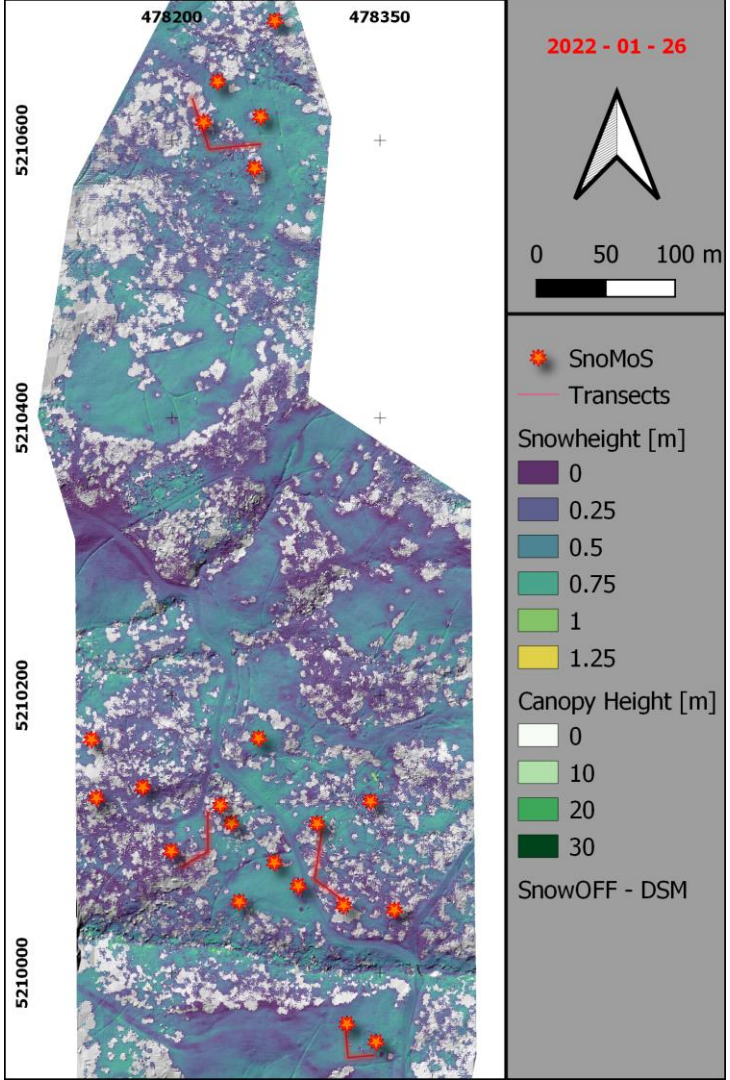

Canopy height [m]
Cluster
SWE_{max} [mm]
0
50
100 m
35
0
1
2
3
4
NA
350
120

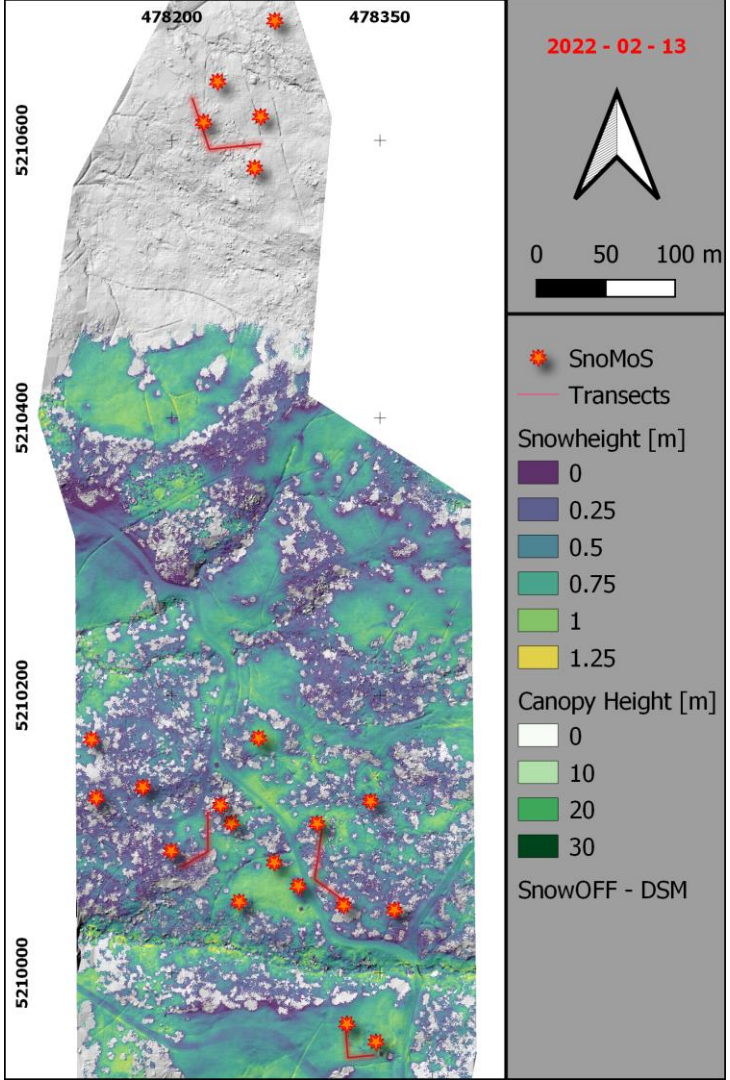


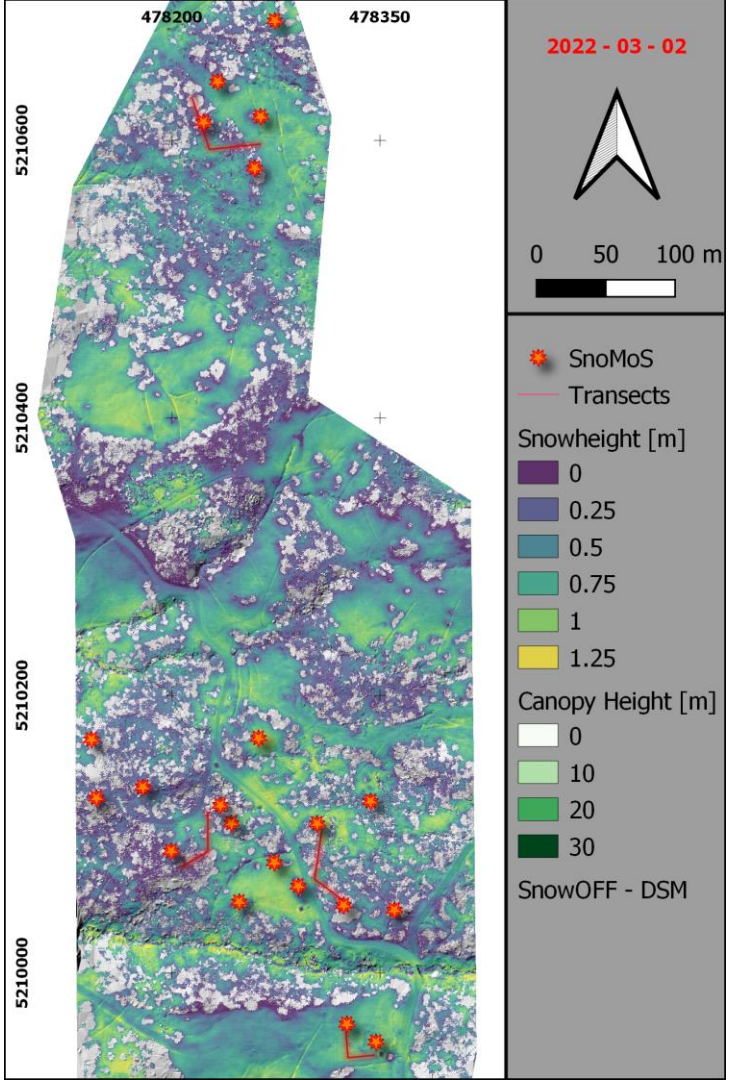

478200
478350
5210600
5210400
5210200
5210000
Observations
0 50 100 m
SnoMoS
Transects
SnowOFF - DSM
Observations
0
1
2
3
4
5
6
7
8

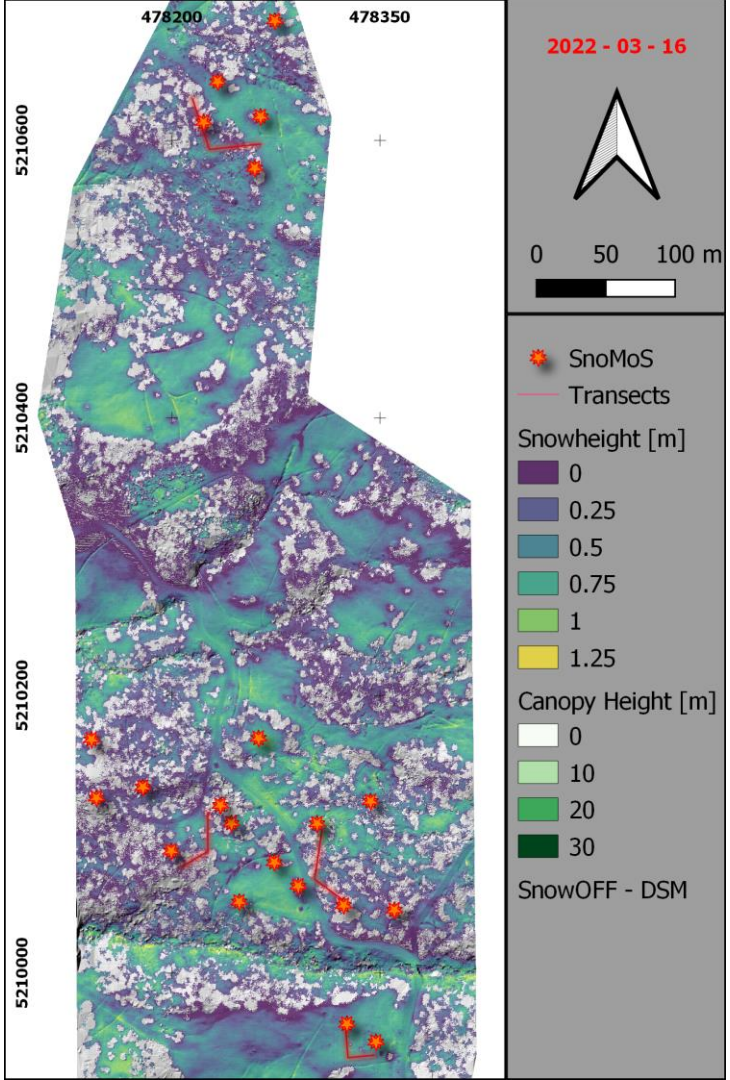

478200
478350
5210600
5210400
5210200
5210000
2021 - 12 - 15
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM

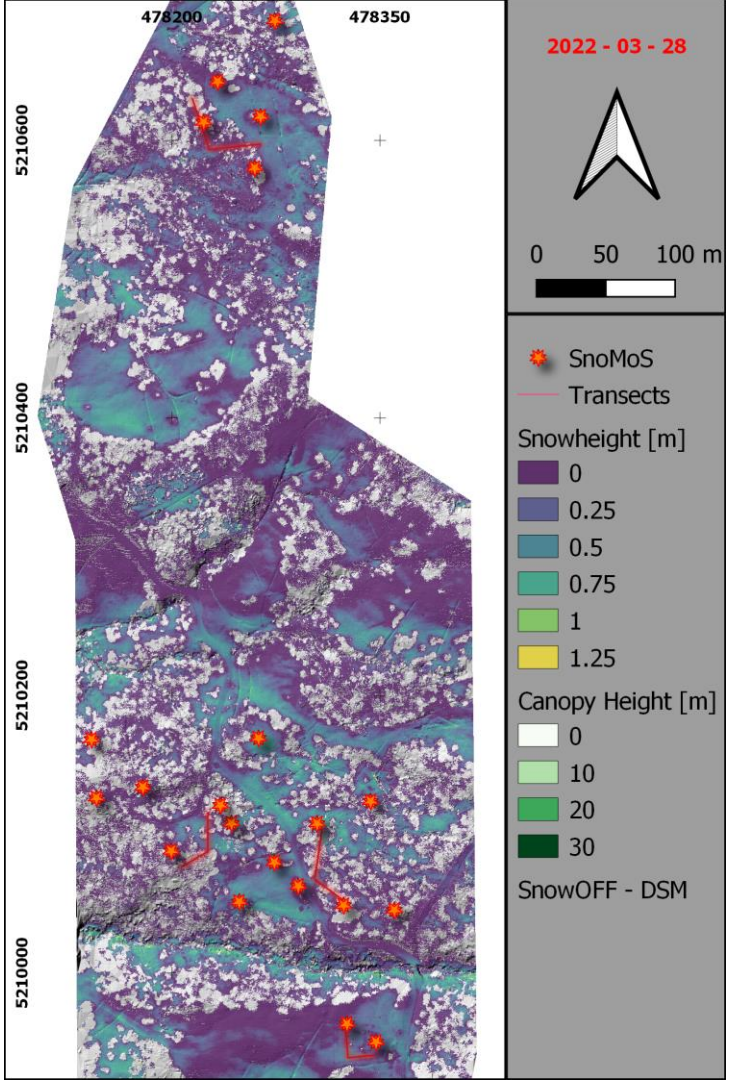

478200
478350
5210600
5210400
5210200
5210000
2022 - 01 - 19
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM

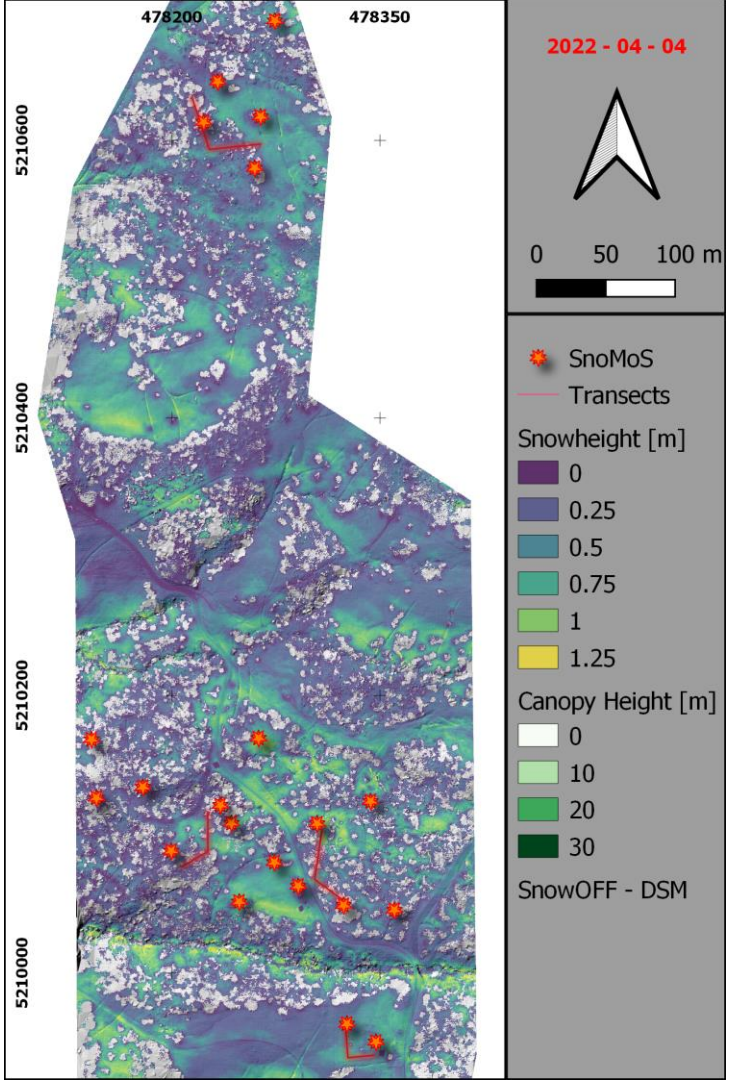

478200
478350
5210600
5210400
5210200
5210000
2022 - 01 - 26
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM


478200
478350
5210600
5210400
5210200
5210000
2022 - 02 - 13
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM


478200
478350
5210600
5210400
5210200
5210000
2022 - 03 - 02
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM


478200
478350
5210600
5210400
5210200
5210000
2022 - 03 - 16
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM


478200
478350
5210600
5210400
5210200
5210000
2022 - 03 - 28
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM


478200
478350
5210600
5210400
5210200
5210000
2022 - 04 - 04
0
50
100 m
SnoMoS
Transects
Snowheight [m]
0
0.25
0.5
0.75
1
1.25
Canopy Height [m]
0
10
20
30
SnowOFF - DSM