Seasonal evaluation of morphological indexes in quantifying snow cover patterns in the Zugspitze area

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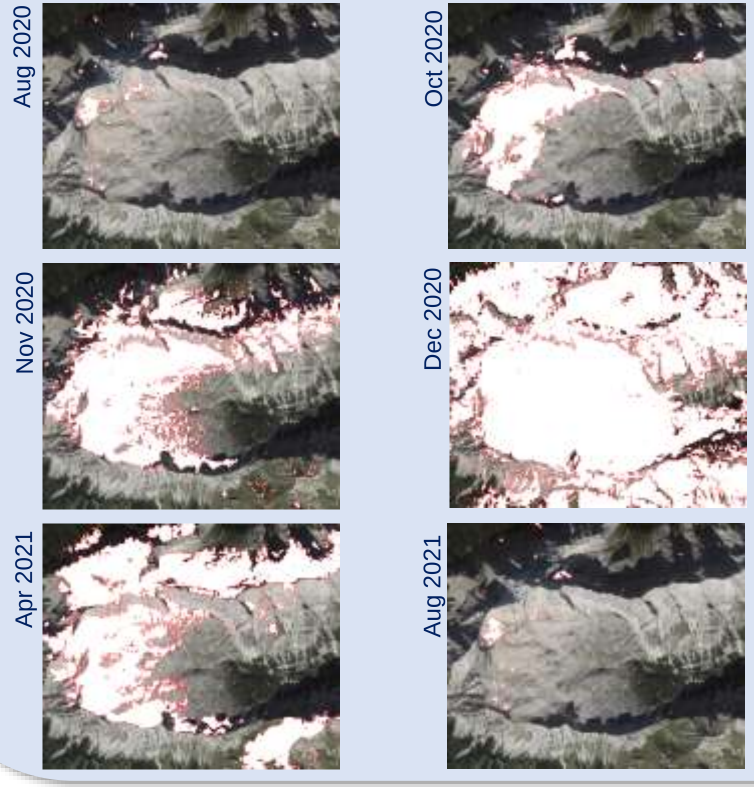
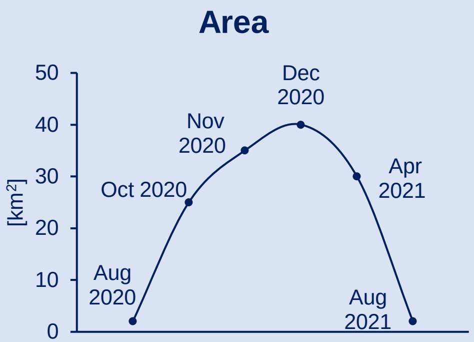
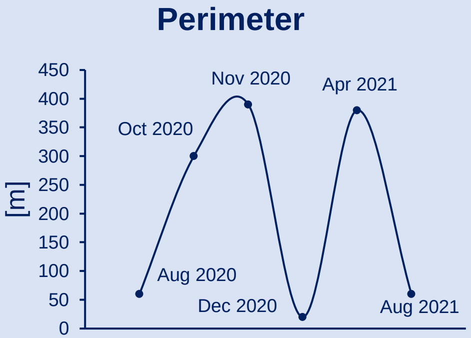
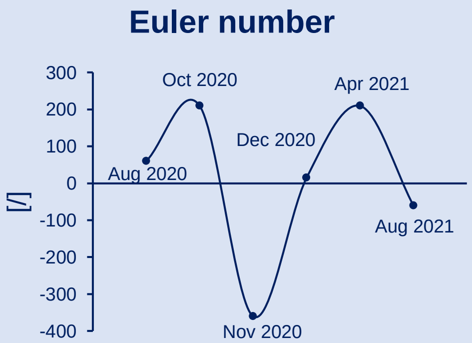
Seasonal change of snow cover patterns shown by Sentinel-2 images for the Zugspitze area, Germany

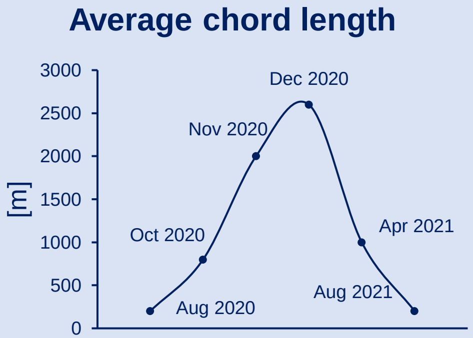


Computation of morphological indexes related to spatial distribution of snow

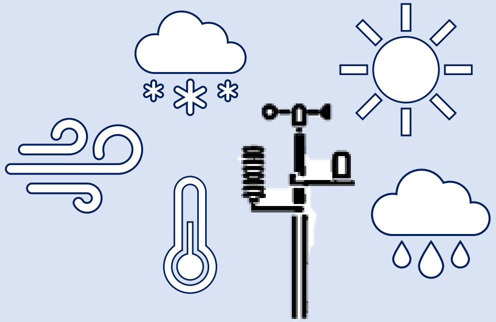








Effect of topography and meteorological variables on snow processes



Motivation

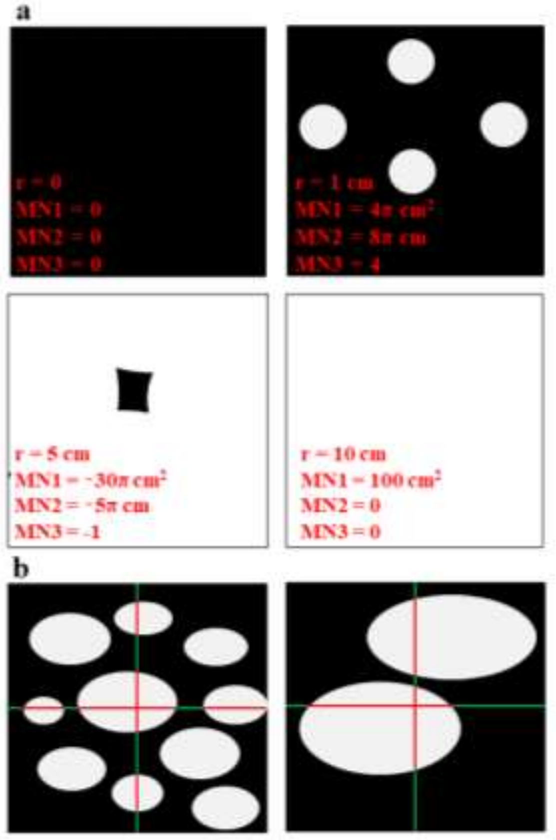
The **spatiotemporal distribution of snow cover has a large impact on many processes at different scales**, including the Earth's energy balance, the hydrological cycle and ecosystems functions. Studying the variability of snow cover in space and time is therefore fundamental to understand the implications that it has on many aspects of the human life. Although it is known that the occurrence of **snow cover patterns is mainly driven by topography and wind**, they are **still complex to describe in their spatial and temporal dynamics**. Moreover, it is difficult to obtain reliable and systematic field measures of their features, as many regions influenced by seasonal snow are difficult to access. However, remote sensing techniques, allow studying snow cover patterns also in complex terrain and testing new approaches to describe such patterns.

Objectives

1. Evaluate the effectiveness of different morphological indexes to quantitatively describe snow cover patterns. Such measures were previously applied to quantify soil porous media patterns and are now applied in the field of snow cover patterns:

Minkowski numbers[1]: Morphological descriptors related to curvature integrals which describe area, perimeter and Euler characteristic of a binary pattern.
Average chord length[2]: Average value of the probability distribution of the lengths of the parallel segments intersecting one phase of a pattern.

2. Quantify the correlation between geometric features of snow cover patterns and topographic features and meteo- and snow-related variables.



(a) Examples of Minkowski numbers: area (MN), perimeter (MN2) and Euler characteristic (MN3) of different synthetic patterns with white circular elements of different radius, r, belonging to an area of 100 cm^2. (b) Schematic of chord length measurements for a cross sections of two-phase random patterns. The chords are defined by the intersection of lines with the two-phase interface. In the examples, two lines of segments in vertical and horizontal directions are represented.

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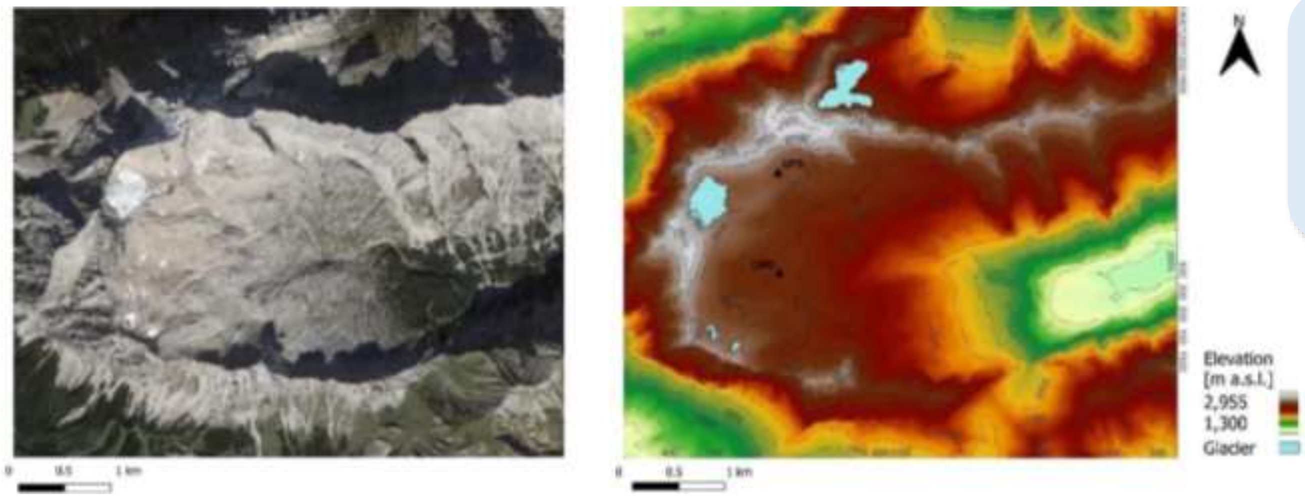
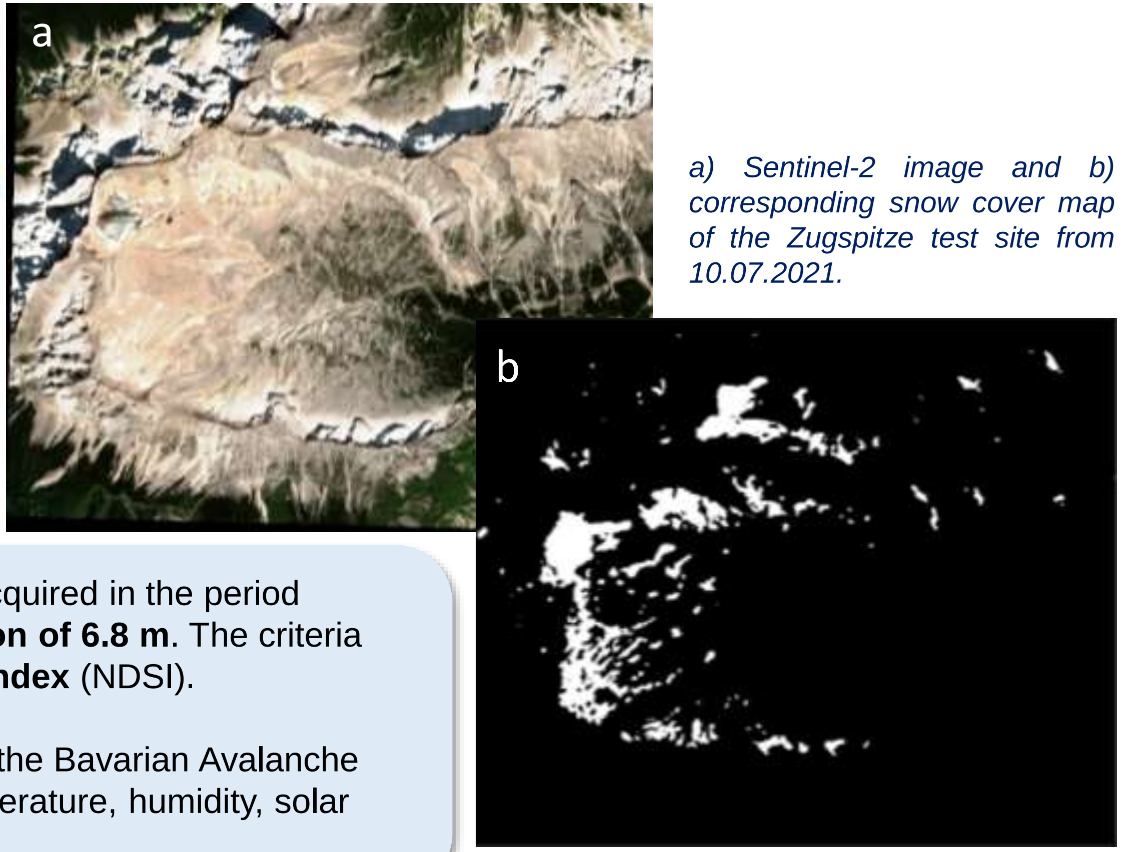
Study site Zugspitze

a b



a) satellite image provided by Google.cn Satellite (2022) of Zugspitze test site; b) spatial distribution of altitude values and locations of: glaciers, LWD automatic weather station and Environmental Research Station Schneefernerhaus (UFS).

The area of interest has an extent of 30 km^2 and fully covers the high-alpine **test site Zugspitze** (Germany/Austria). The catchment is **snow-dominated** and characterized by a **high topographic variability** and limited vegetation. The highest point in the area of interest is at 2962 m a.s.l. and the lowest point at ~850 m a.s.l.;



a) Sentinel-2 image and b) corresponding snow cover map of the Zugspitze test site from 10.07.2021.

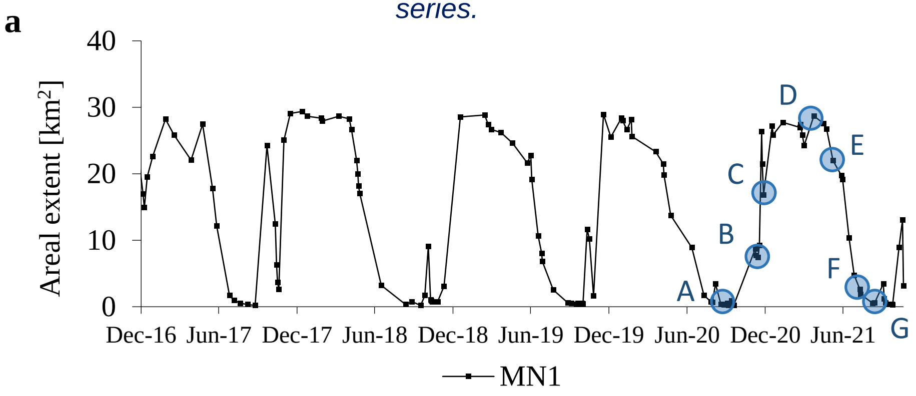
Data

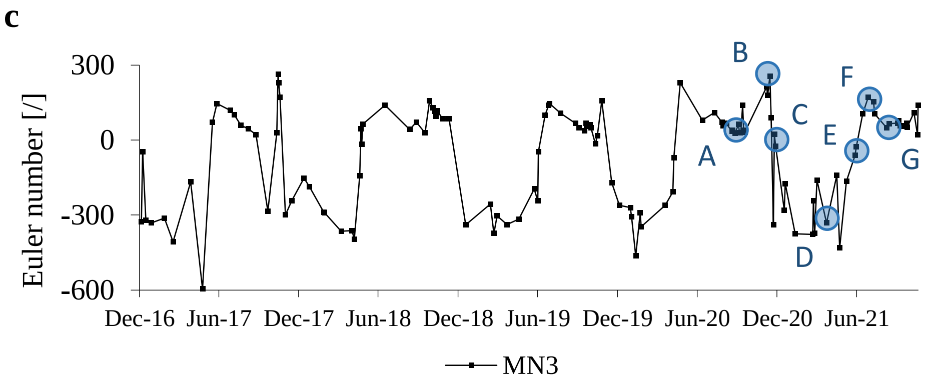
- **Snow cover maps** of the study site derived from Sentinel-2 satellite images acquired in the period between **November 2016 – October 2021** (129 days), with a **spatial resolution of 6.8 m**. The criteria applied for snow identification is based on the **Normalized Difference Snow Index** (NDSI).
- **Digital Elevation Model** (DEM) with spatial resolution of 1 m
- **Meteo and snow data** acquired by the LWD station Zugsptizplatt operated by the Bavarian Avalanche Service (e.g. Snow Water Equivalent (SWE), snow depth, air and surface temperature, humidity, solar radiation…)

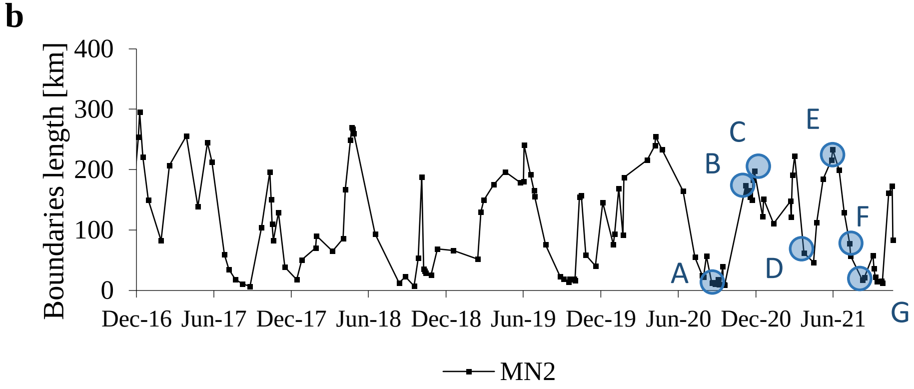
Temporal evolution of the morphological indexes

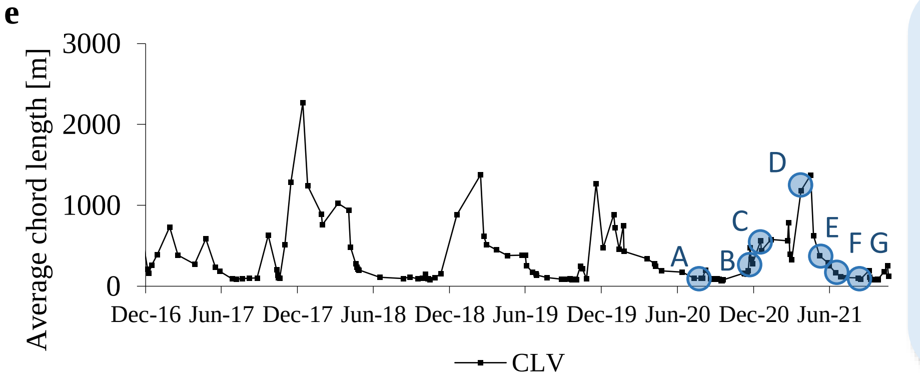
The temporal variability of the **geometry of the snow cover patterns** was analysed by **computing the indexes on the entire area** of interest

Examples of snow cover maps for different times of the season and corresponding values of the indexes in the time series.









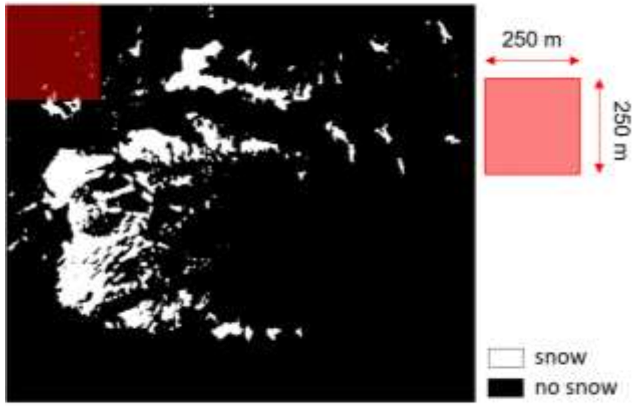
	MN2	MN3	CL
MN1	0.516	-0.847	0.769
MN2		-0.234	-0.003
MN3			-0.639

Linear correlation coefficients computed between every indexes show a certain level of independence from each other meaning additional and complementary information on the snow patterns in each one of them.

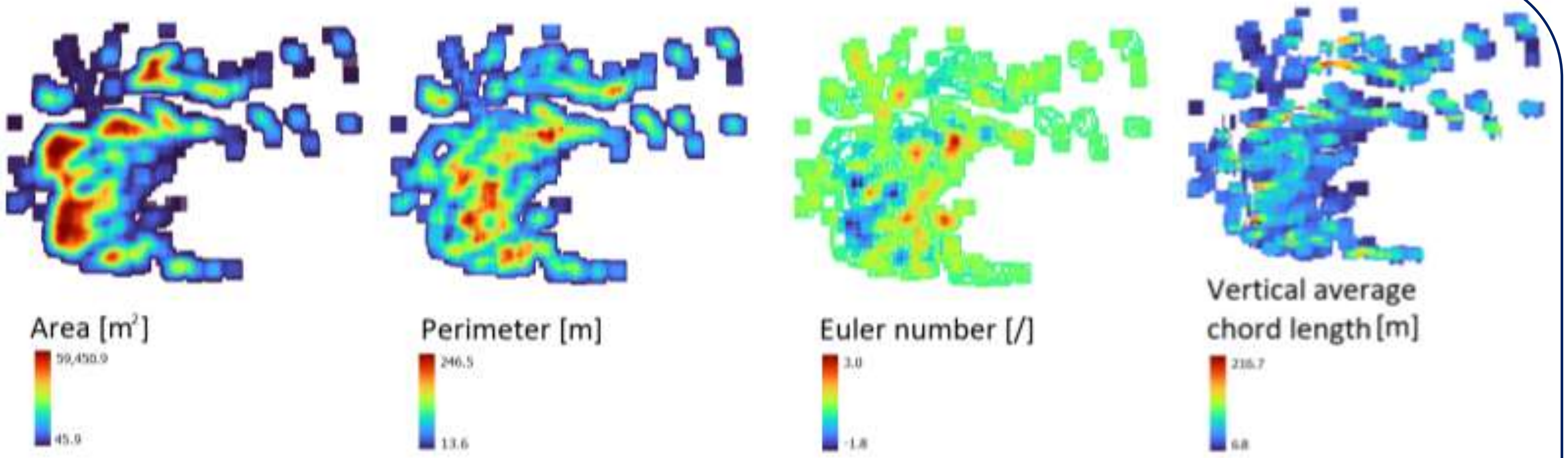
Time series of the Minkowsky numbers: area (MN1), perimeter (MN2), Euler number (MN3) and the Average chord length (CL) computed on snow cover maps of the study site Zugspitze between Nov-2016 and Oct-2021. Results show **good capacity** of the indexes to **describe** the **temporal variability** of the snow patterns and their **seasonality** and **annual periodicity**

Spatial distribution of the morphological indexes and topography

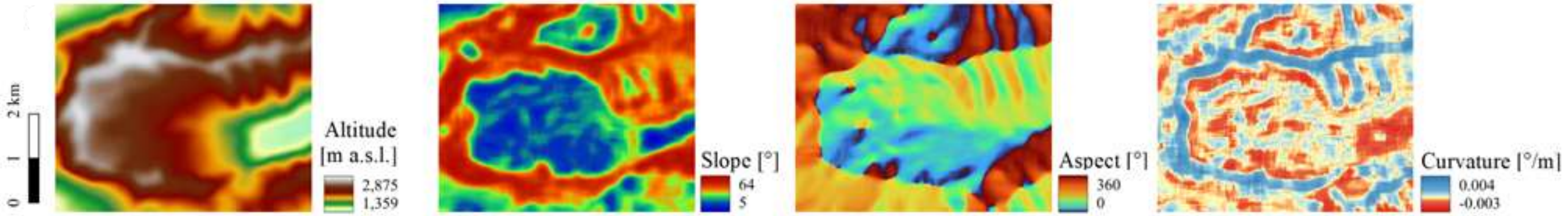
A **moving window algorithm** (window size: 250m x 250m) was developed to compute the **spatial distribution** of the **morphological indexes** (Minkowski numbers and Average chord length) and the **topographic features** (e.g. altitude, slope, aspect, curvature…) within the area of investigation, to assess the **spatial correlation** between snow **cover pattern geometric features** and **topographic features** of the ground.



Schematic of application of the moving window algorithm on a snow cover map (note: the size of the window in the animation is not to scale with the snow cover map)



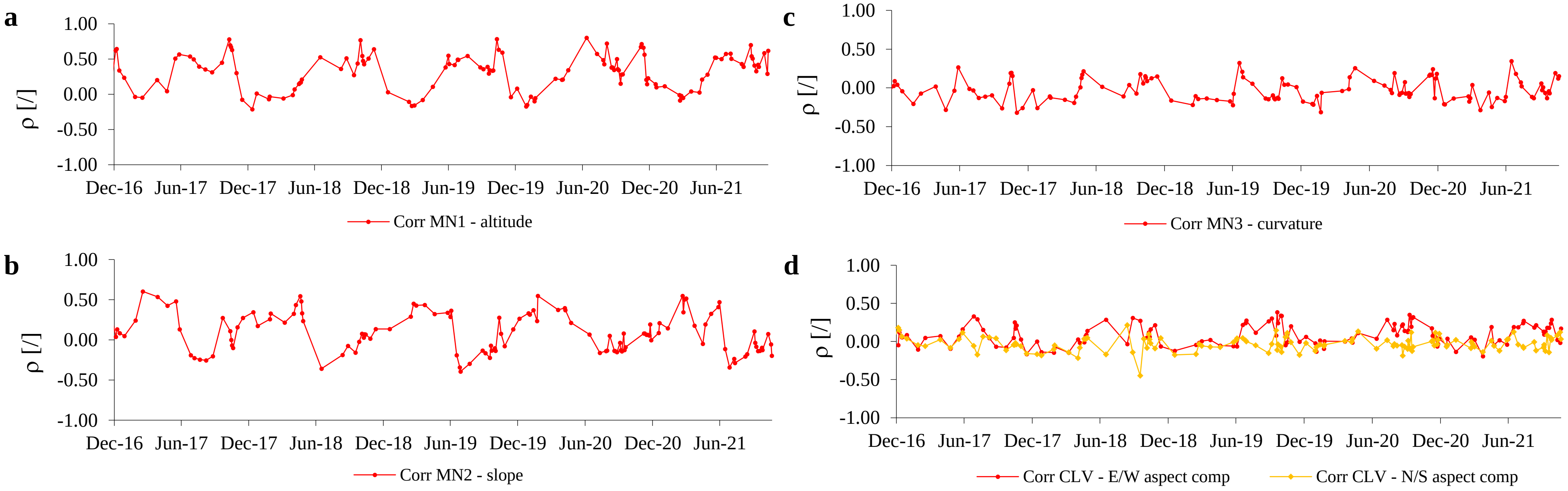
Spatial distribution of the morphological indexes computed with the moving window algorithm on the snow cover map of 14/11/2020. The spatial distribution of each index was computed for every snow cover map available in the period Nov-2016 Oct-2021.



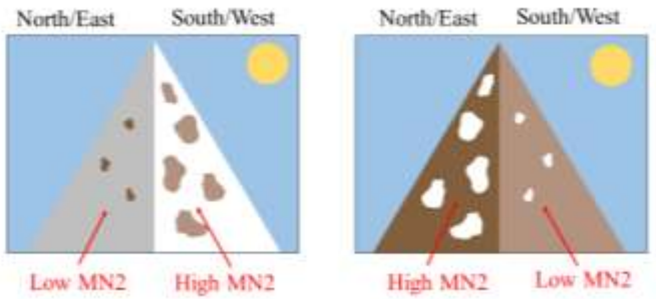
Spatial distribution of averaged topographic descriptors computed with the moving window algorithm on the Digital Elevation Model of the study site. The size of the window is the same of the one applied for the snow cover maps, to obtain comparable information.

Spatial correlation of morphological indexes with topography

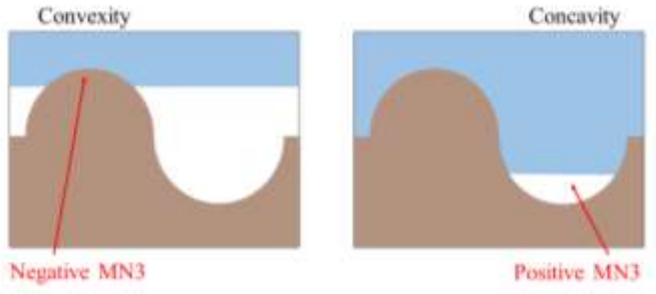
The spatial correlation between **morphological indexes** and **topographic descriptors** was quantified by the **Spearman coefficient** (r). Preliminary results show a **good level of correlation** at certain times of the year and a **marked periodic behaviour**. Depending on the time of the season, the descriptors can show positive or negative correlations.



Examples of timeseries of correlation values between the morphological indexes and some topographic features (a) correlation between area (MN1) and altitude, (b) correlation between perimeter (MN2) and slope, (c) correlation between Euler characteristic (MN3) and curvature, (d) correlation between Average chord length (CLV) and the north-south and the east-west components of aspect.



Schematic of why snow patterns show highest MN2 values at low values of aspect (south/west) when there is an extended snow cover, and highest MN2 values at high values of aspect (north/east) when there is a limited snow cover.

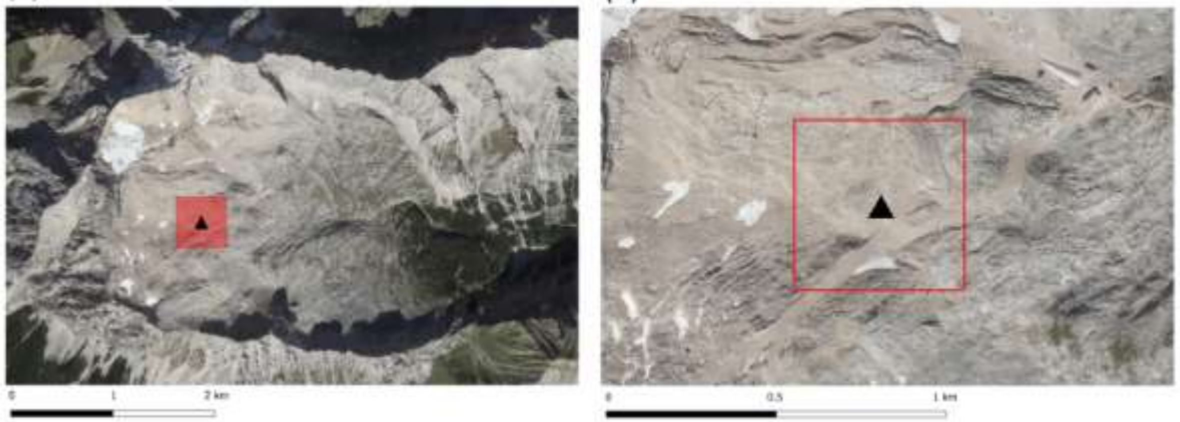


Schematic of why snow patterns show negative values of MN3 on convex ground when there is an extended snow cover, and positive values of MN3 on concave ground when there is a limited snow cover.

Highest correlation observed during **ablation** (Apr-Jul) and **accumulation** (Sep-Dec), suggesting highest impact of topography on snow distribution in these periods.
Lowest correlation values observed during **high winter** (homogeneous snow cover extents) and **summertime** (almost no snow in the area).

Temporal correlation of morphological indexes with meteorological and snow-related variables

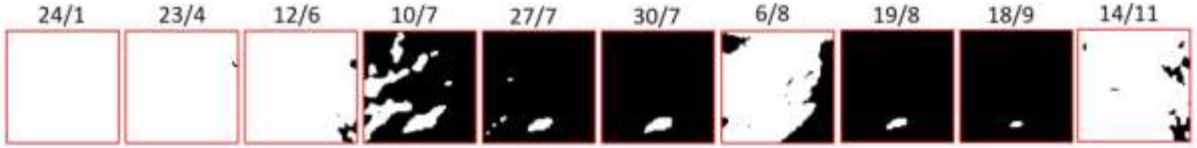
(a) (b)



(a) position of the LWD station and the area used for the computation of the snow cover pattern descriptors in the Zugspitze study area; (b) area of 500m x 500m selected for the computation of the snow cover pattern descriptors. Satellite image on the background provided by Google.cn Satellite (2022).

To compute the morphological indexes on the snow cover patterns to compare to the meteorological and snow-related variables, it was considered an area of 500 m x 500 m centered on the LWD station.

(c)



(c) Examples of snow cover maps of the area of interest computed on Sentinel-2 images acquired during 2020.

A correlation between the morphological indexes and meteorological and snow data is of great interest, because it could be a step forward on the estimation of **snow parameters** which are generally difficult to retrieve (like **Snow Water Equivalent** and **snow height**), through **remote sensing imaging**.

Variables showing the highest correlation values:

	Meteo and snow-related variables	*Area*	*Perimeter*	*Euler number*	*Average chord length*
***Daily** average values*	*Daily average Snow Water Equivalent*	0.56	0.13	-0.42	0.44
	Daily average Snow Height	0.56	-0.10	-0.33	0.17
Average** values of previous **2 weeks	*2 weeks average air temperature*	-0.56	-0.04	0.19	-0.37
	2 weeks average relative humidity	-0.30	-0.03	0.25	-0.29
	2 weeks average surface temperature	-0.63	-0.15	0.40	-0.54
Cumulated** values of previous **2 weeks	*2 weeks snow accumulation*	0.42	-0.02	-0.15	0.59
	2 weeks snow ablation	0.38	0.42	-0.50	0.35
	2 weeks increase in SWE	0.52	0.25	-0.09	0.15
	2 weeks decrease in SWE	0.38	0.34	-0.53	0.48

Conclusions

The morphological indexes, Minkowsky numbers and average chord length, **were able to describe geometric features of snow cover patterns** and show a **meaningful correlation with topographic descriptors and meteo and snow variables**. However, some topographic features and meteo and snow variables (e.g. altitude, temperature, SWE) showed a stronger effect than others (e.g. curvature).

Outlook

The first results look promising, however, further investigation would be valuable, e.g. by applying **smaller scales** and a **more frequent temporal resolution** (e.g., with web-cams), including spatially **distributed meteo and snow** information and **comparing with fractional snow-covered area (fSCA)** approaches.

References

[1] *ARMSTRONG, R. T., MCCLURE, J. E. & ROBINS, V. 2019. Porous Media Characterization Using Minkowsky Functionals: Theories, Applications and Future Directions. Transport in Porous Media, 130, 305–335.*

[2] *ROBERTS, A. P. & TORQUATO, S. 1999. Chord distribution functions of three-dimensional random media: Approximate first-passage times of Gaussian processes. Physical Review E.*

Zugspitze catchment webcam image provided by Bayerische Zugspitzbahn Bergbahn AG (zugspitze.de)