A comparison of snow depth scaling patterns from TLS, UAV and Pleiades observations

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EGU General Assembly
#EGU24
14 -19 April 2024

Introduction:

- Since the emergence of LiDAR technology, a deeper understanding of the snow spatial patterns has been achieved exploiting **variogram analysis** to find distinct **fractal patterns in snow scaling behaviour** (Lehning et al., 2011; Fassnacht &Deems 2006,;Deems et al., 2006; Scipion et al.; 2013, Mott et al., 2011)

Variogram: examine the degree of spatial dependency

Semivariance for distance h $\hat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{(i,j) \in N(h)} (z_j - z_i)^2$

If self-similar behaviour of snow depth exists

It is possible to fit power law (Deems et al., 2006)

$$\gamma(h) = \alpha h^{\beta}.$$

Fractal dimension

$$D = 3 - \frac{\beta}{2}.$$

"Measure of an object to fill the space in which resides" (Sun et al., 2006)

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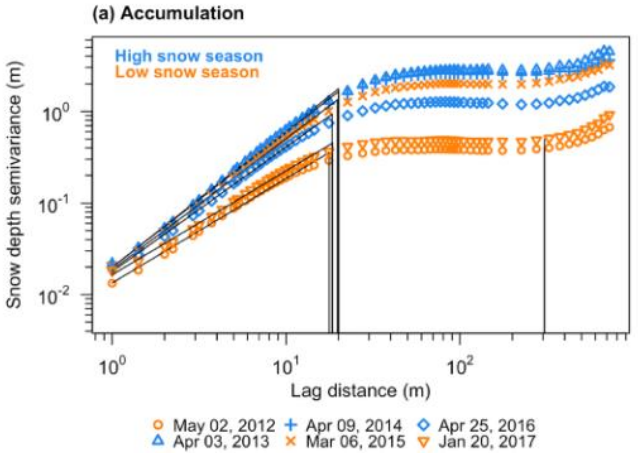

Fractal dimension

"Measure of an object to fill the space in which resides" (Sun et al., 2006)

Introduction:

- Some studies investigated the **temporal consistency in the spatial structure** of snow (Clemenzi et al., 2018; Deems et al., 2008; Helficcht et ., 2014; Schirmer & Lehning, 2011)

  - These studies reported **similar scales break**s (10 to 35 m) and **fractal dimensions** (2.34-2.66 for short ranges and > 2.9 for long ranges) across years but **did not cover multiple periods**.

  - Main **wind direction** was identified as a key control for **directionality** and **anisotropy**.

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Are snow fractal patterns and scale breaks consistent over several years?

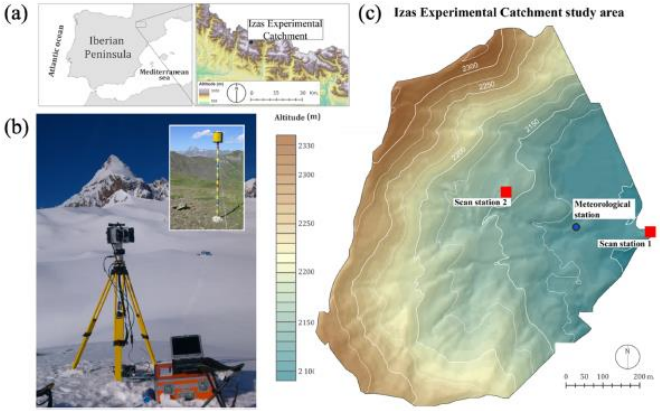
Introduction:

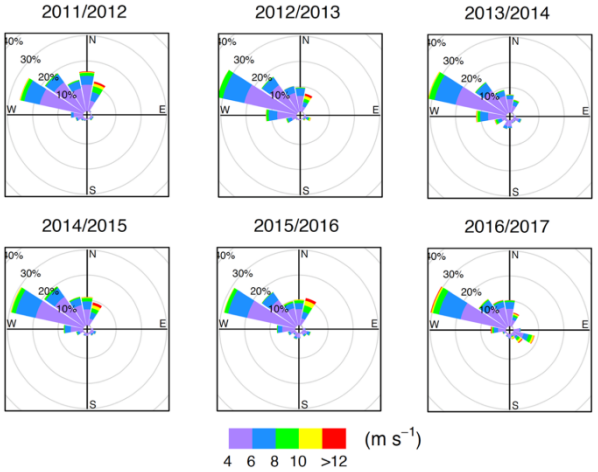
Earth Syst. Sci. Data, 9, 993–1005, 2017
https://doi.org/10.5194/essd-9-993-2017

Open Access Earth System Science Data

Meteorological and snow distribution data in the Izas Experimental Catchment (Spanish Pyrenees) from 2011 to 2017

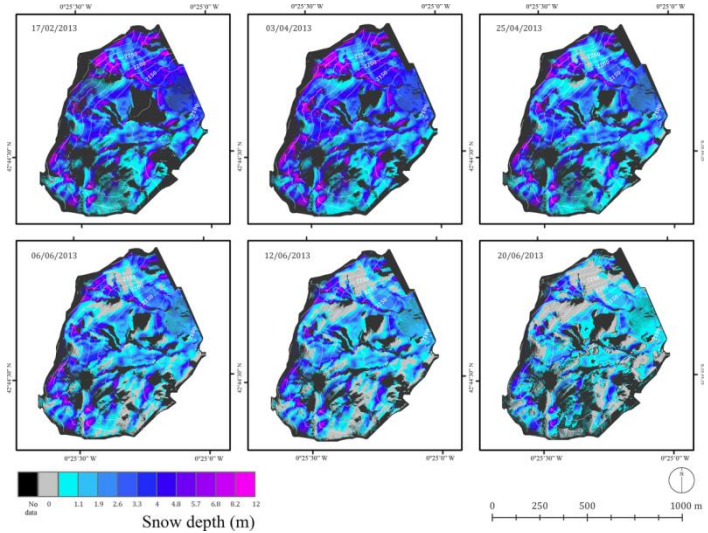
Jesús Revuelto[1,2], Cesar Azorin-Molina[1,3], Esteban Alonso-González[1], Alba Sanmiguel-Vallelado[1], Francisco Navarro-Serrano[1], Ibai Rico[1,4], and Juan Ignacio López-Moreno[1]





Izas cathcment

- 55 ha
- 2000-2300 m
- 6 years of LiDAR observations
- Available continuous meteorological observations



Introduction:

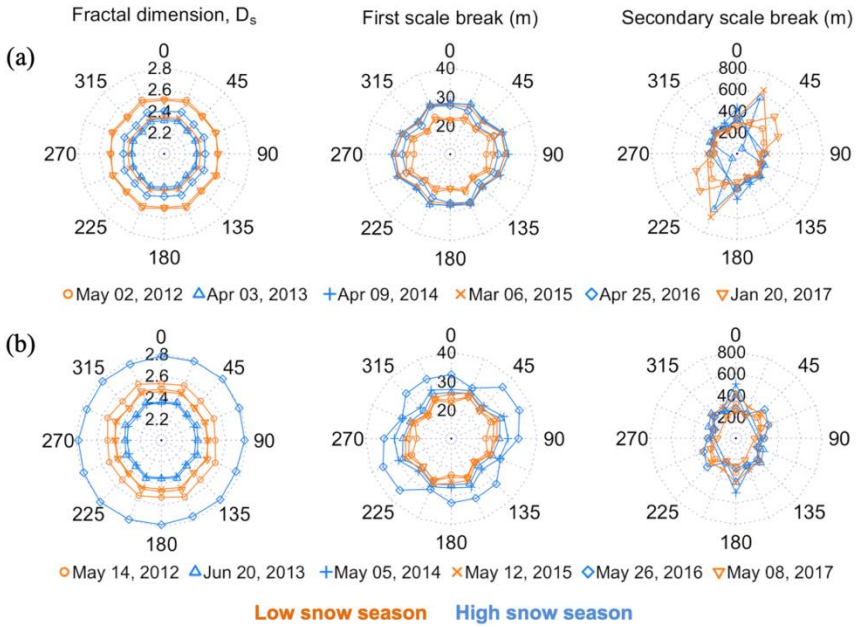
Water Resources Research

RESEARCH ARTICLE
10.1029/2020WR027343

Special Section:
Advances in remote sensing, measurement, and simulation

Interannual and Seasonal Variability of Snow Depth Scaling Behavior in a Subalpine Catchment

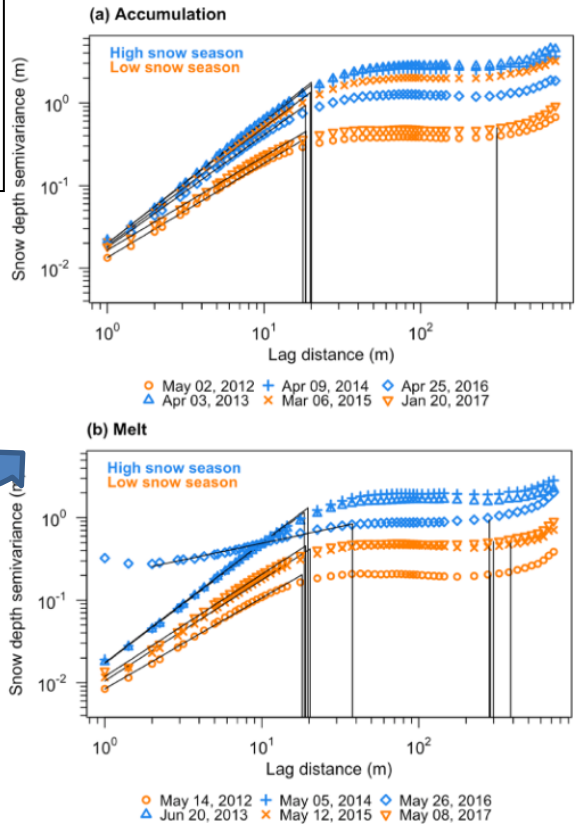
Pablo A. Mendoza[1,2], Keith N. Musselman[3], Jesús Revuelto[4], Jeffrey S. Deems[5], J. Ignacio López-Moreno[4], and James McPhee[1,2]



Omnidirecional analysis

Directional analysis

$$\hat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{(i,j) \in N(h)} (z_j - z_i)^2$$



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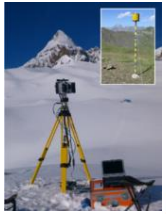
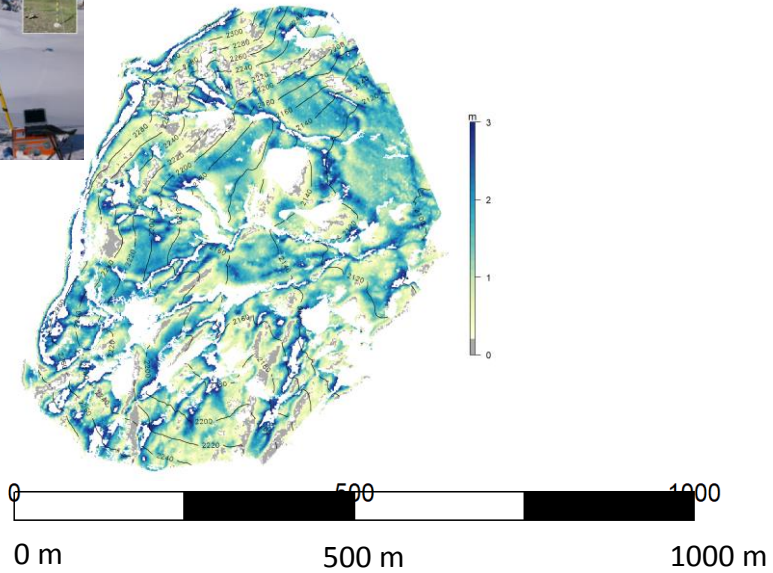


Variogram computed up to 750 m (diameter of the largest circle inside the domain)



- Consistent short-range fractal behavior and scale breaks in snow depth.
  - Fractal parameter 2.25-2.85
  - Scale breaks 17-24 m
- Scale break anisotropies in shallow snowpacks might be explained by bare-earth terrain scaling patterns
- A second scale break is observed in some dates, but **the extent of the observations might limit its identification**

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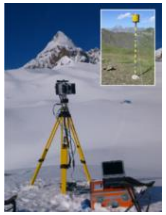

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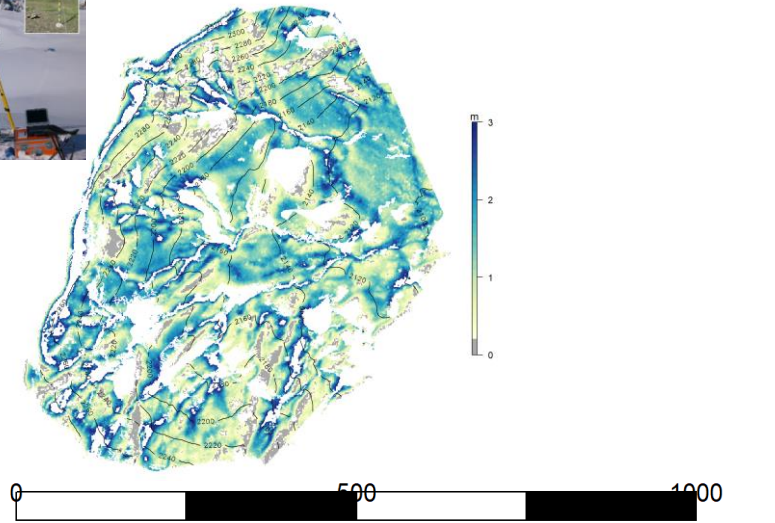

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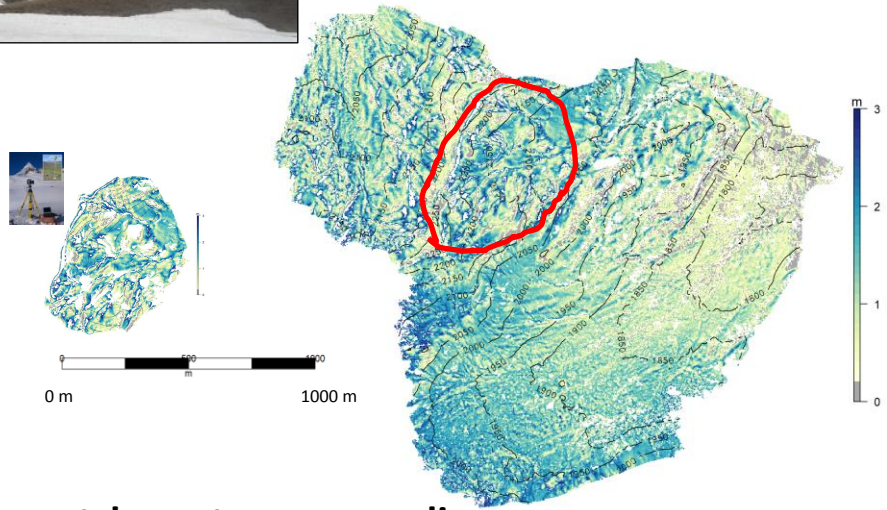
Scaling properties of snow depth over larger domains: Is there a second scale break?

New observations available:

UAV acquistions

Variogram computed up to 2000 m (before 750 m)



Water Resources Research

RESEARCH ARTICLE
10.1029/2020WR028980

Special Section:
Advances in Remote Sensing, Measurement, and Simulation of Seasonal Snow

Key Points:

Light and Shadow in Mapping Alpine Snowpack With Unmanned Aerial Vehicles in the Absence of Ground Control Points

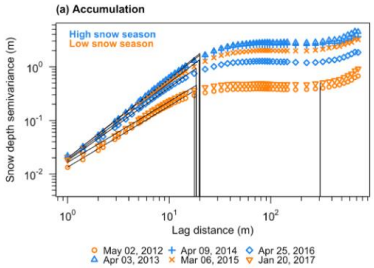
Jesús Revuelto[1], Juan Ignacio López-Moreno[1], and Esteban Alonso-González[1]

[1]Instituto Pirenaico de Ecología, IPE-CSIC, Zaragoza, Spain

Izas catchment + surrounding areas

- 300 ha (before 50 ha)
- 1700-2300 m (before 2000-2300 m)
- 4 years of UAV observations (30 acquisitions)

New observations available:



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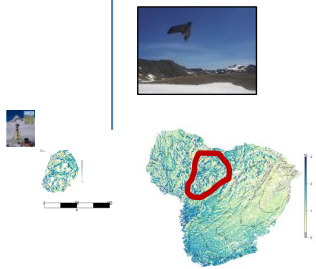
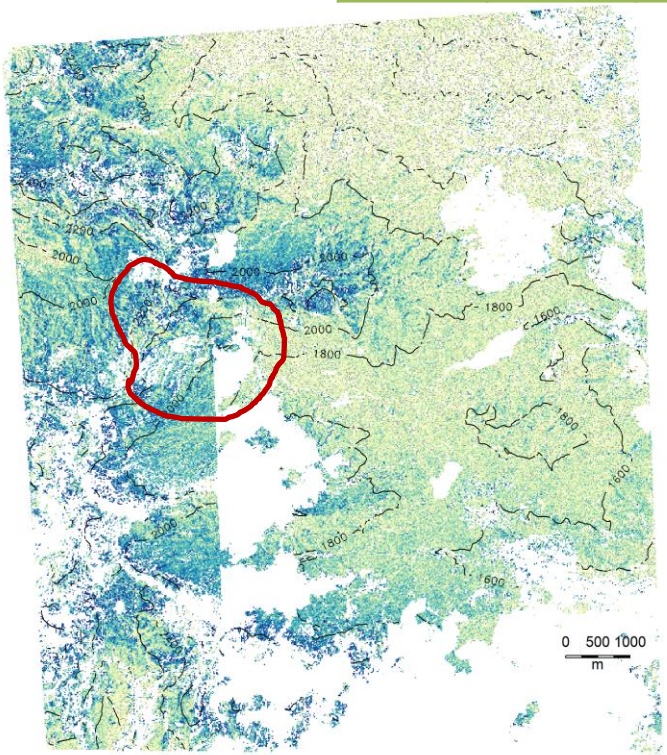
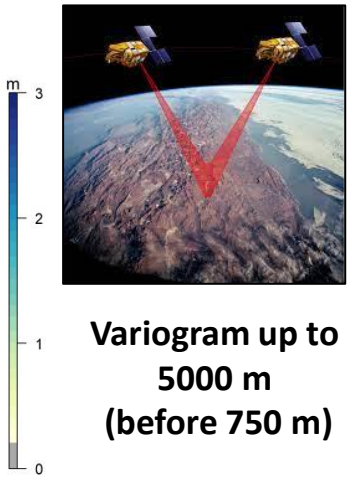


Snow season	Date	Mean SD [m]	Std dev. [m]	SCA [%]
2019-20	19-Feb	1,28	1,09	91
2021-22	27-Jan	1,34	1,15	90
	11-May	1,06	1,07	86
2022-23	15-Feb	1,07	0,88	91



Pleiades acquistions



Variogram up to 5000 m (before 750 m)

Izas catchment + + surrounding areas

- > 5000 ha (before 50 ha)
- 1600-2600 m (before 2000-2300 m)
- 4 acquisitions (3 seasons)

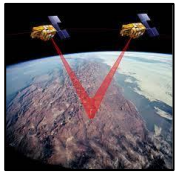
Dataset of observations:

	Date	Mean_SD (m)	SCA_(%)
	14/01/2020	1,07	0,94
	03/02/2020	1,29	0,95
	24/02/2020	1,15	0,86
	11/03/2020	1,52	0,94
	24/04/2020	1,19	0,54
	29/04/2020	1,23	0,63
	03/05/2020	1,12	0,38
	12/05/2020	1,07	0,24
	19/05/2020	1,03	0,22
	26/05/2020	0,78	0,11
2019-2020	02/06/2020	0,51	0,15
	02/02/2021	1,45	0,72
	04/03/2021	1,29	0,89
	23/03/2021	1,18	0,79
	14/04/2021	1,05	0,45
	04/05/2021	1,03	0,33
	20/05/2021	0,63	0,42
2020-2021	08/06/2021	0,40	0,23
	16/12/2021	1,19	0,93
	12/01/2022	1,12	0,81
	28/01/2022	1,17	0,86
	18/02/2022	1,11	0,79
	17/04/2022	1,20	0,51
2021-2022	16/05/2022	1,06	0,21
	01/12/2022	0,45	0,36
	13/02/2023	0,98	0,89
	16/03/2023	0,81	0,59
	28/03/2023	0,74	0,42
	20/04/2023	0,74	0,23
2022-2023	02/05/2023	0,55	0,17

Izas experimental catchment:

Snow depth observation at 1m spatial resolution

- ✓ 25 LiDAR (TLS) observations along 6 years (50ha)
- ✓ 30 UAV observations along 4 years (300 ha)
- ✓ 4 Pleiades observations (4000 ha)



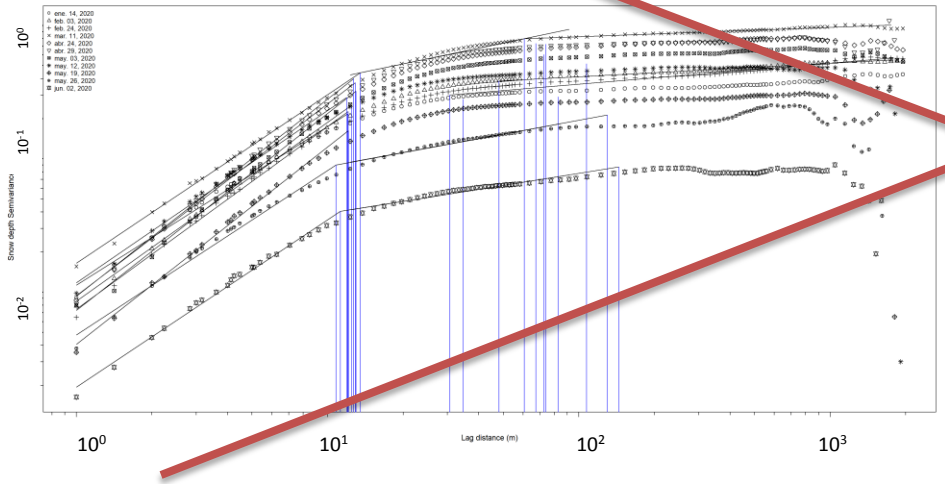
	date	Mean_SD (m)	SCA_(%)
	19/02/2020	1,3839703	0,9146534
	27/01/2022	1,47784332	0,89705363
	11/05/2022	1,21500199	0,85638582
Pleiades	15/02/2023	1,16509544	0,90635196

Example: snow year 2019-2020

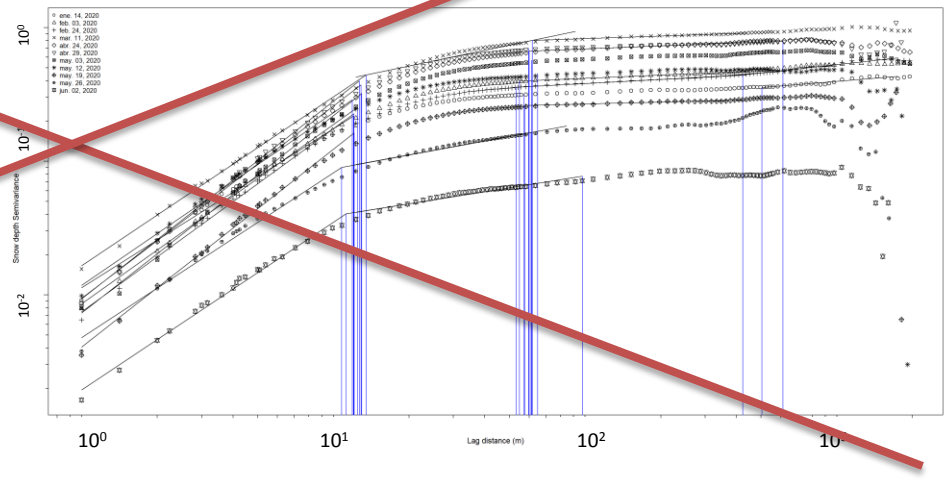
When we try to identify two or three scale breaks the distances are not constant among UAV surveys or the linear adjustments are not reliable ➔ NOT found second scale break

Snow season	Date	Mean SD [m]	Std dev. [m]	SCA [%]
2019-2020	14-Jan	1,01	0,63	94
	3-Feb	1,23	0,72	95
	24-Feb	1,00	0,73	86
	11-Mar	1,43	0,98	94
	24-Apr	0,67	0,85	54
	29-Apr	0,80	0,88	63
	3-May	0,46	0,73	38
	12-May	0,27	0,58	24
	19-May	0,29	0,53	22
	26-May	0,11	0,34	11

Looking for 2 scales breaks

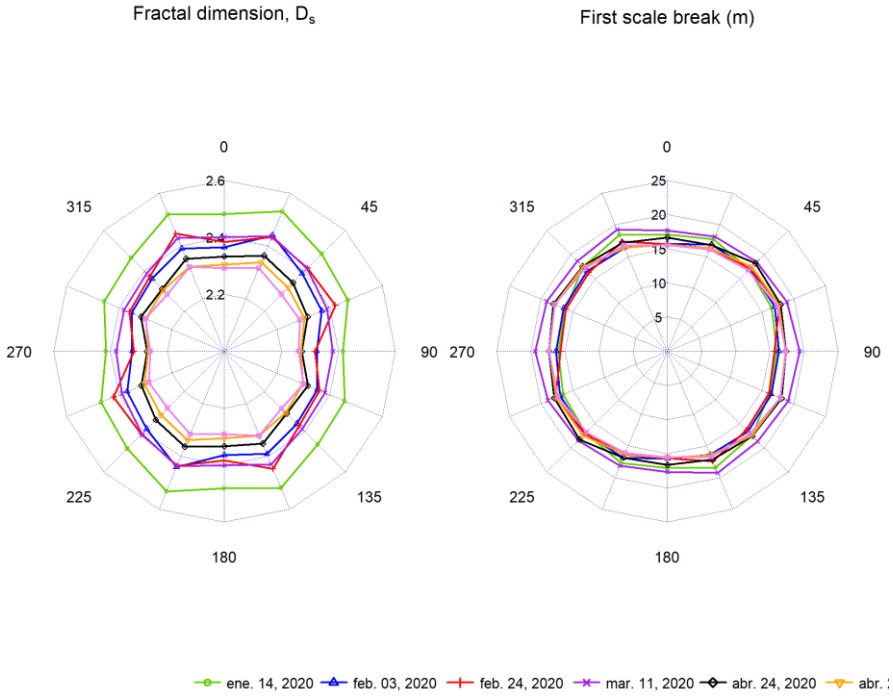


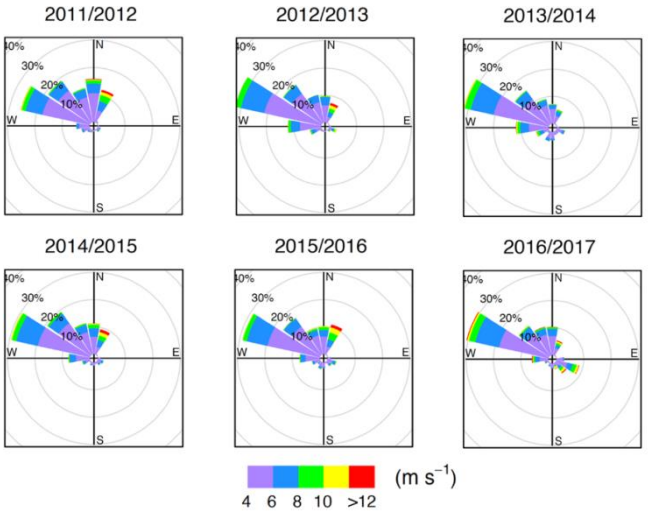
Looking for 3 scales breaks



UAV semivariograms 2019 -020: Directional variogram

Not a consistent directionality is found among surveys despite prevaling wind direction





Previous conclusions:

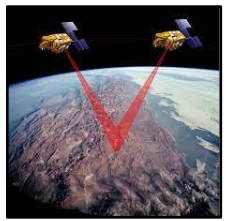
- **Novel snow depth observations** enable to capture **scales** not affordable some years ago.

- **Temporal consistency** of **first scale break** and **fractal dimension** along **10 years** in both **small (LiDAR)** and **medium (UAV)** domains.
  - ✓ 25 LiDAR observations along 6 years
  - ✓ 30 UAV observations along 4 years.

Scaling properties of snow depth over larger domains: Is there a second scale break?

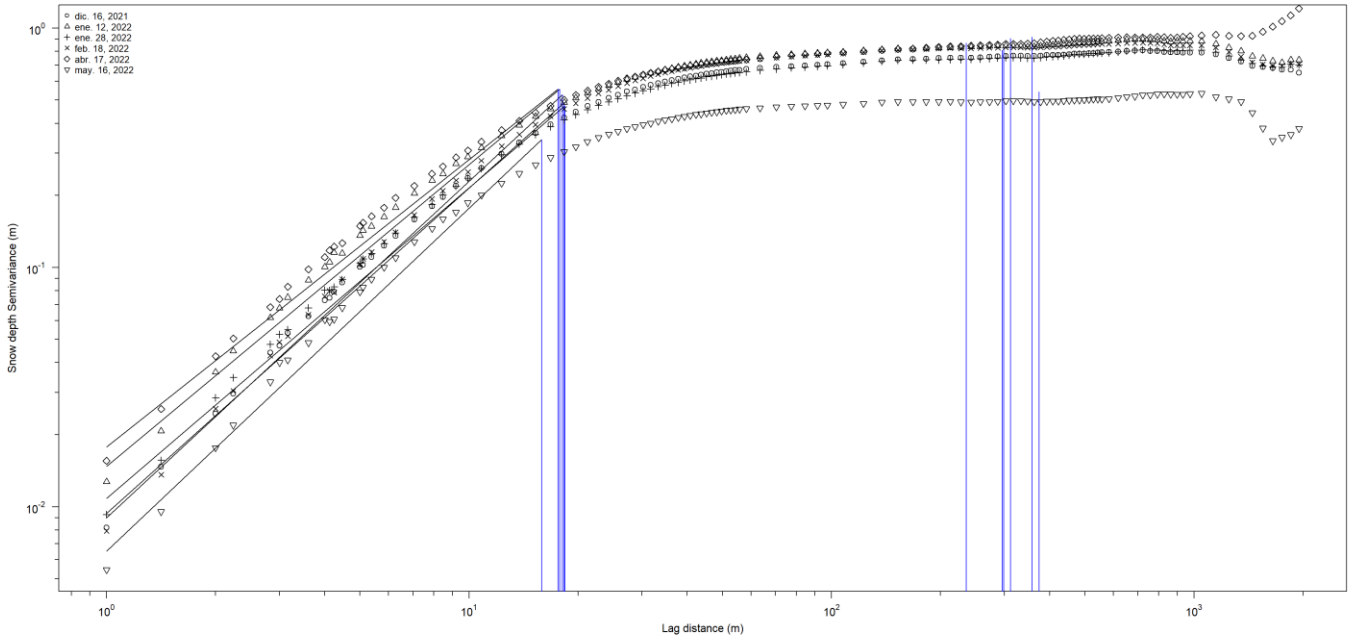
Second scale break barely identified in **few days with no temporal consistency**

- **No remarkable directional dependence** observed of these scales breaks in the study area.



UAV observation semivariograms 2020 acquisitions

	1st Scale Break (m)
14/01/2020	16,9
03/02/2020	17,3
24/02/2020	16,6
11/03/2020	20,3
24/04/2020	18,2
29/04/2020	17,7
03/05/2020	18
12/05/2020	16,5
19/05/2020	16,3
26/05/2020	15,9

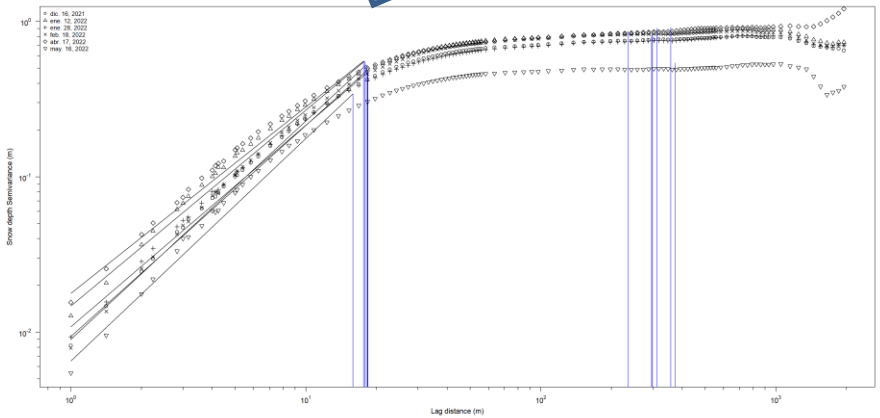


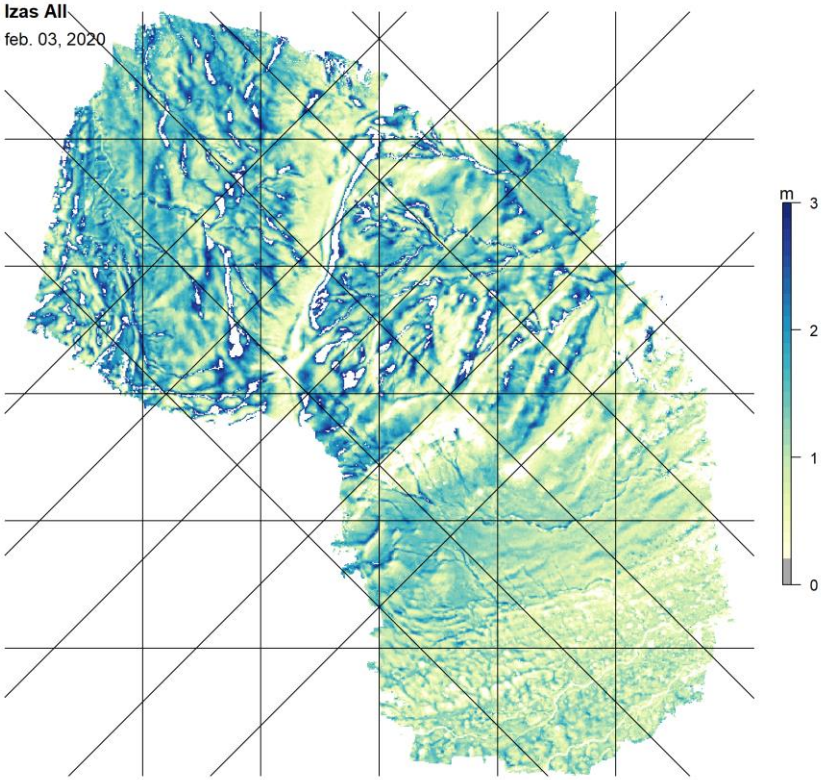
New objectives:

- Identify **scale breaks** with **topography** and **distance between snow accumulation peaks**
- Same results with **different techniques**? (TLS, UAV and Pleiades)

➢ ANALYSIS

Comparison of peak snow depth distance in 4 directions and 1st scale break





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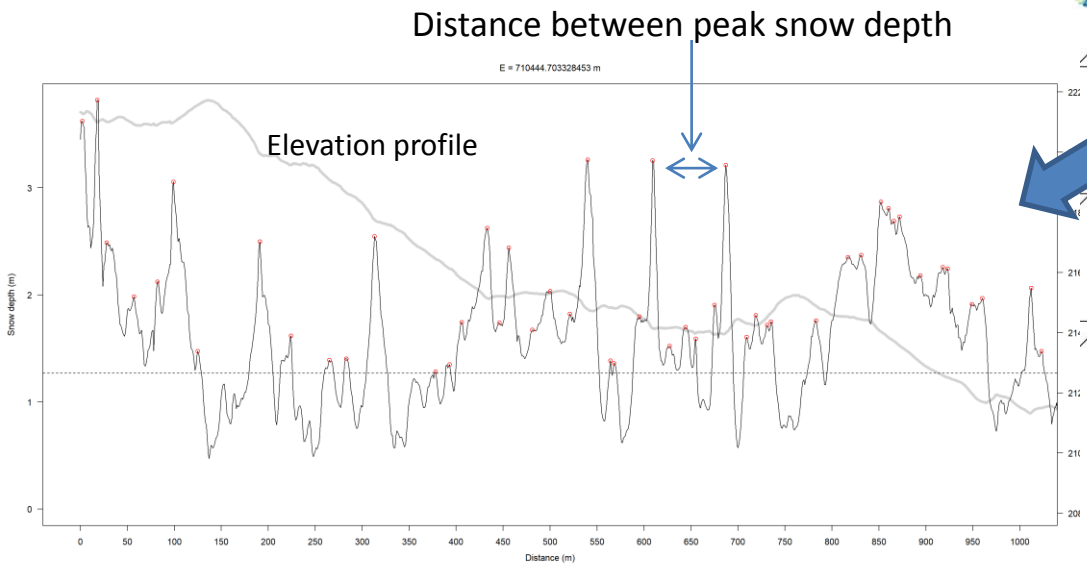

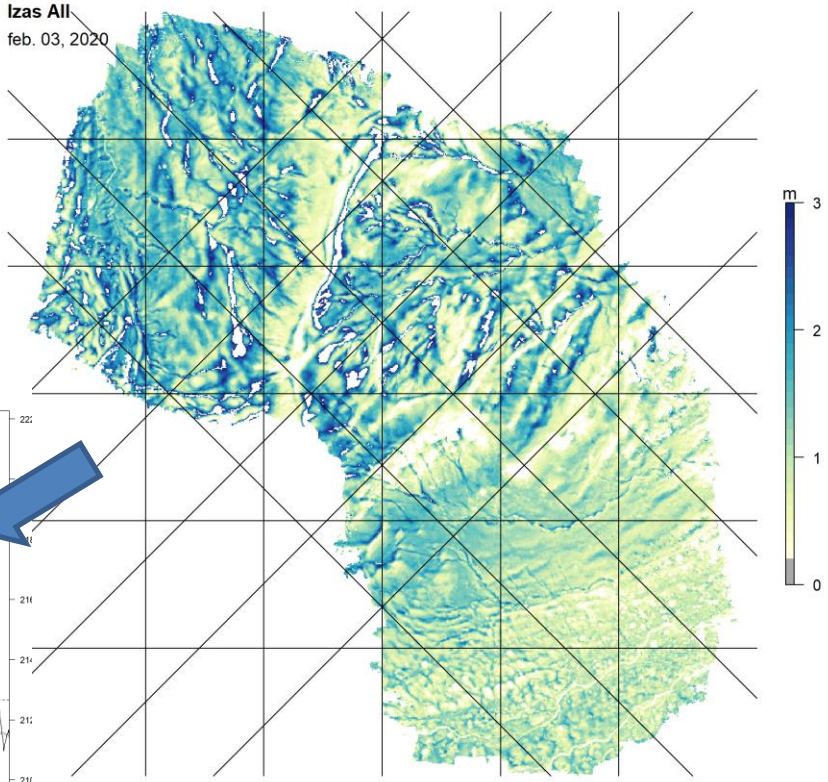

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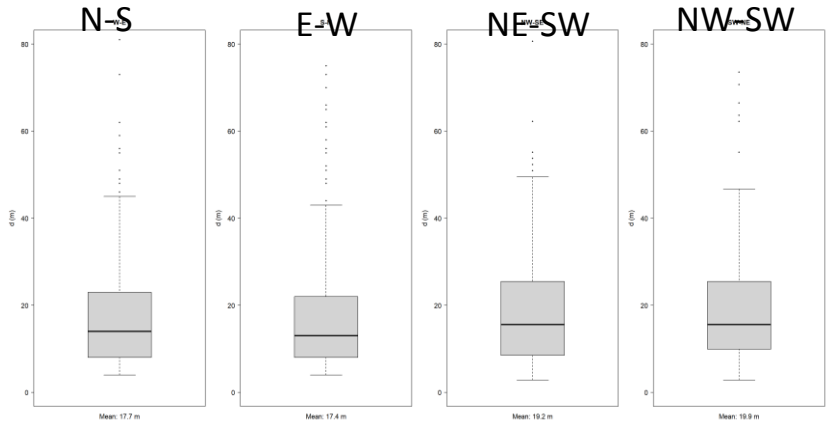
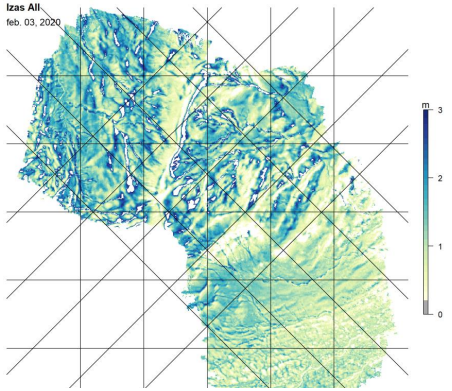
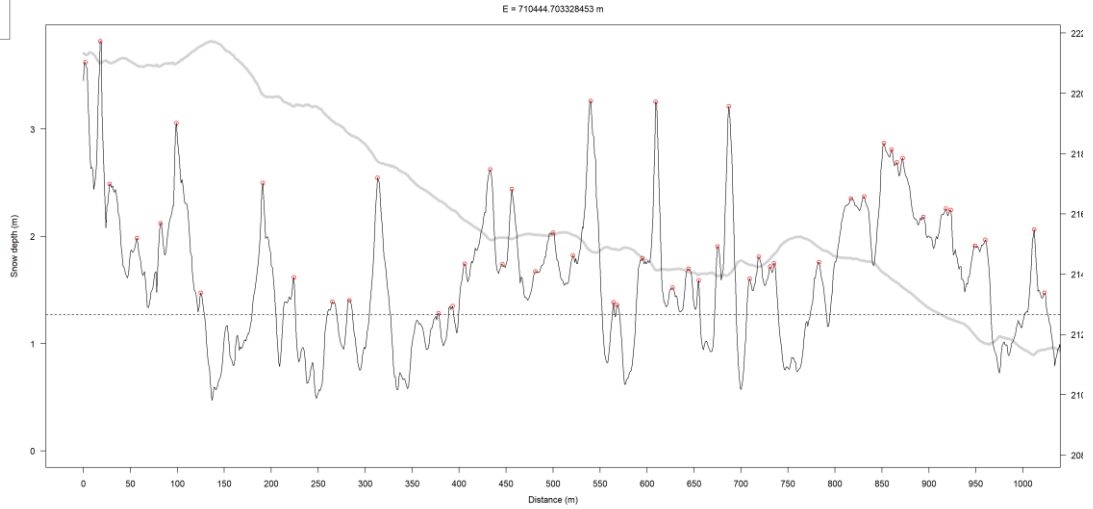






Median distance between peak snow accumulation in 4 directions:

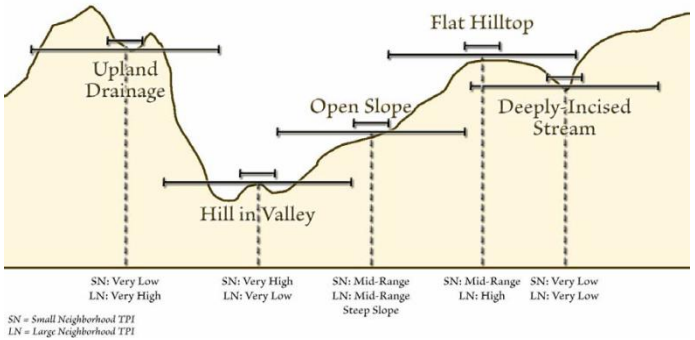
- Ranging from 10 to 20m depending on the UAV acquisition date

➢ ANALYSIS

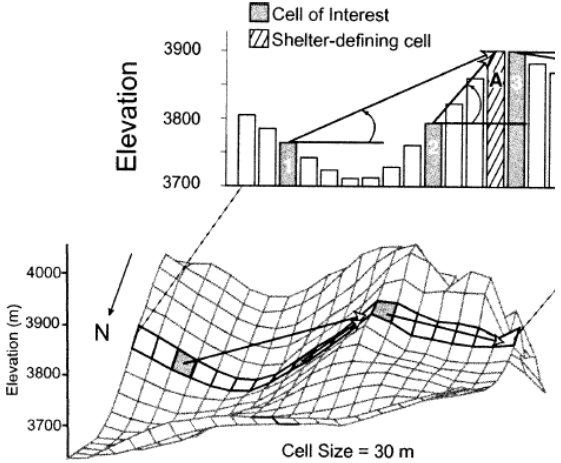
Is there any control on the scale breaks of topographic variables?

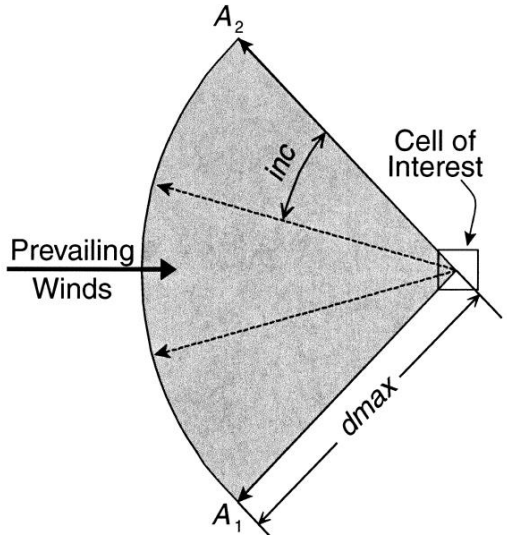
Analyzed elevation, solar radiation, TPI (several search distances), Sx (several distances and directions)

- *Topographic Position Index (TPI,* Weiss, 2001*)*



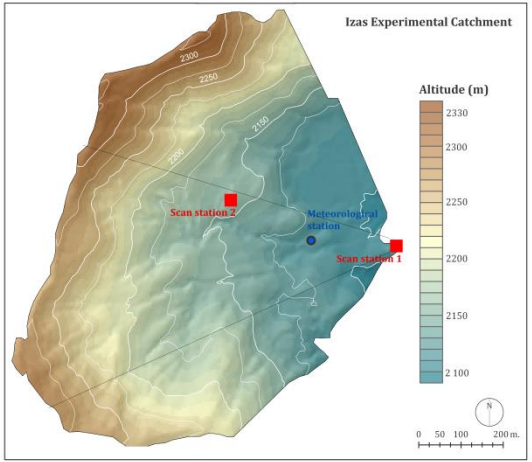
- *Maximum upwind slope (Sx,* Winstral et al., 2002)

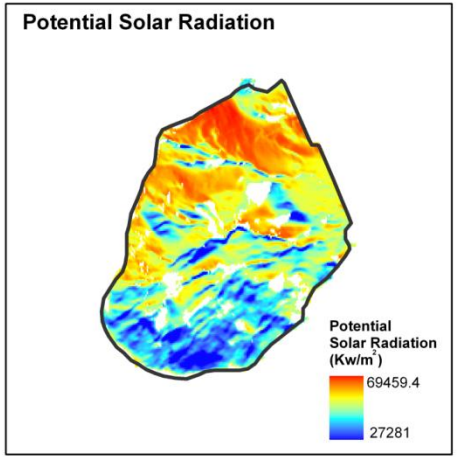


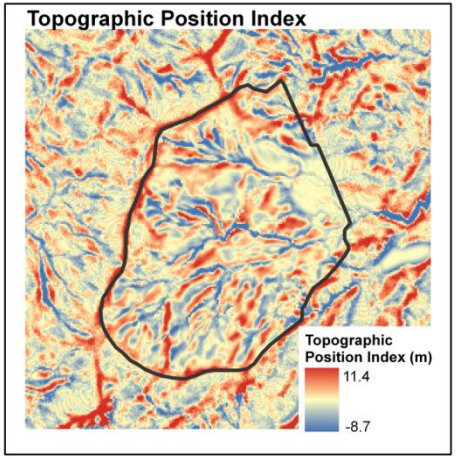


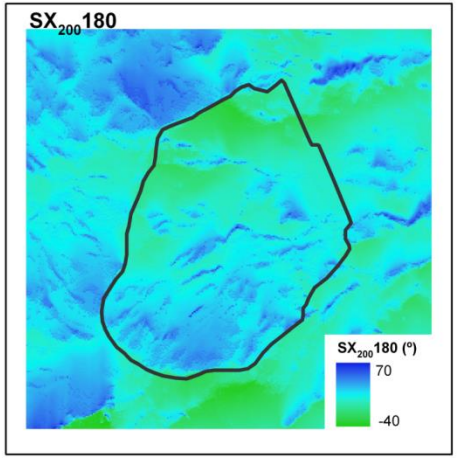
➢ ANALYSIS

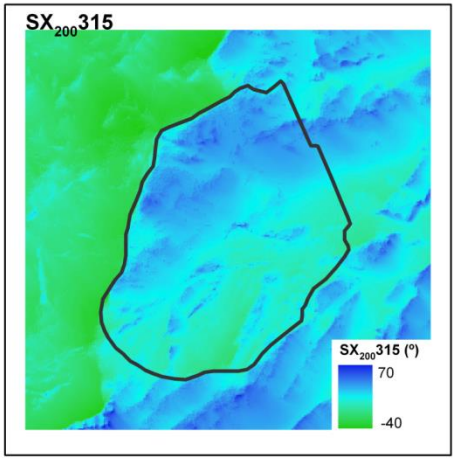
Examples of topographic variables derived from the DEM





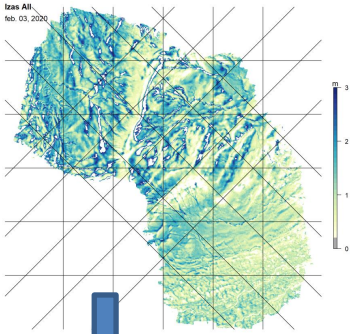




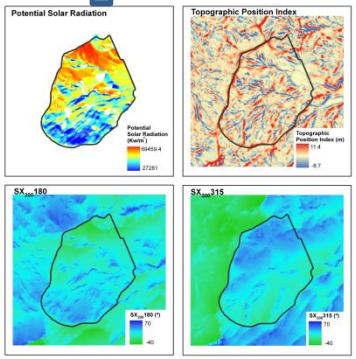


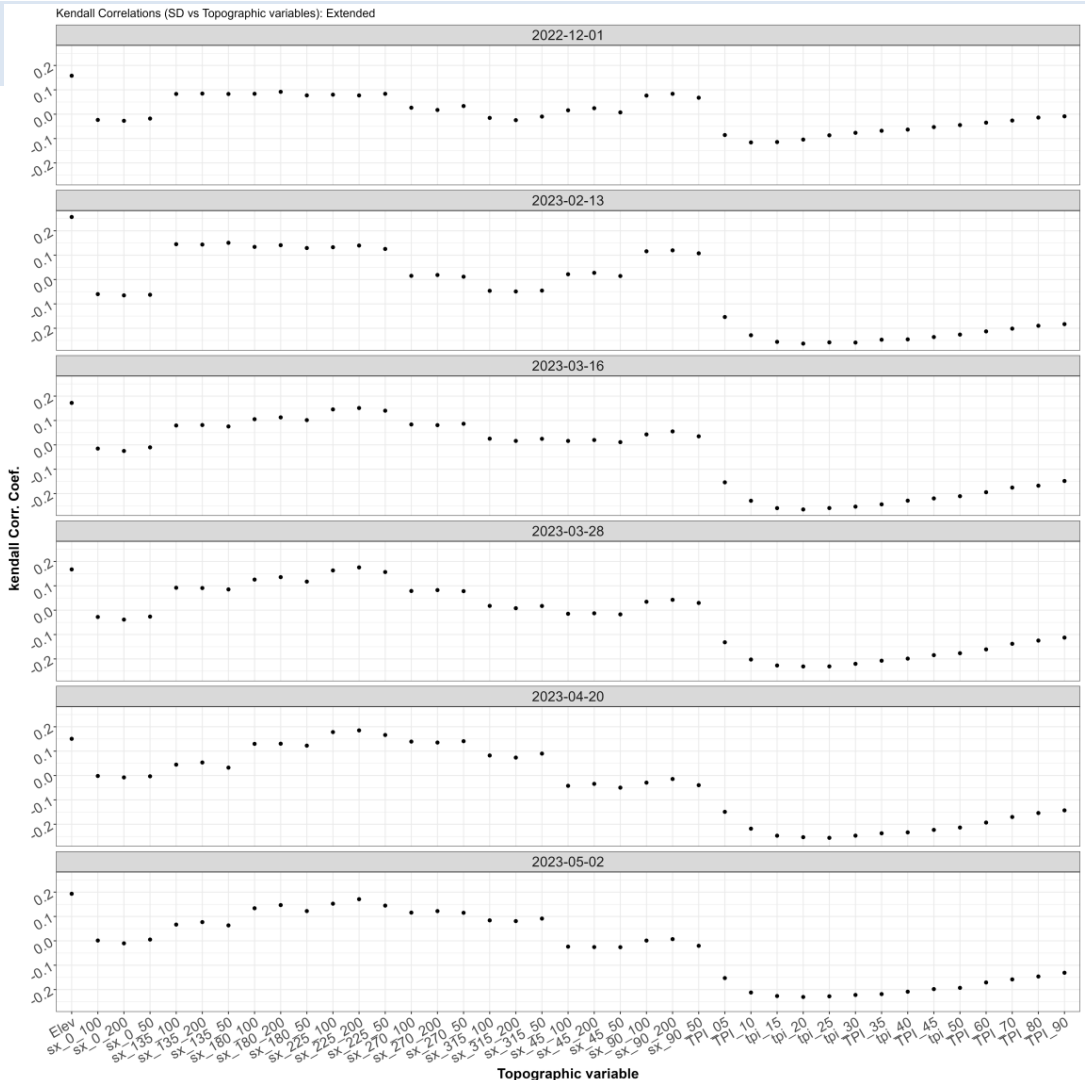
Snow depth scaling patterns from TLS, UAV and Pleiades

- ANALYSIS



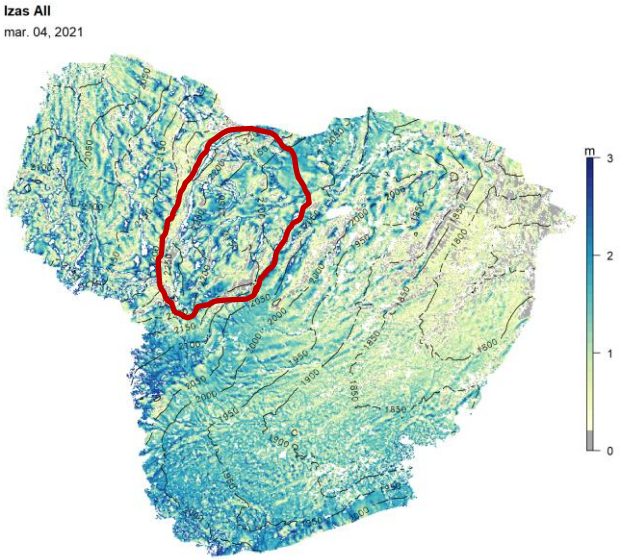
Pearson correlation (snow depth vs topo.)





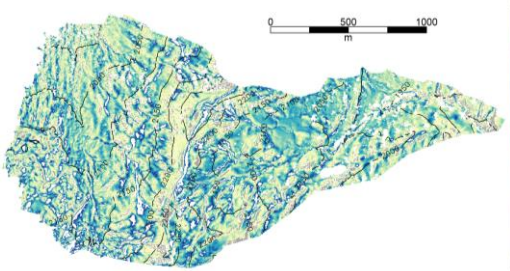
Can we define manually HRU?? (Hydrologic Response Units)

- Are there marked differences in the analysis depending on these limits?
- Do we obtain similar results depending on observation technique?

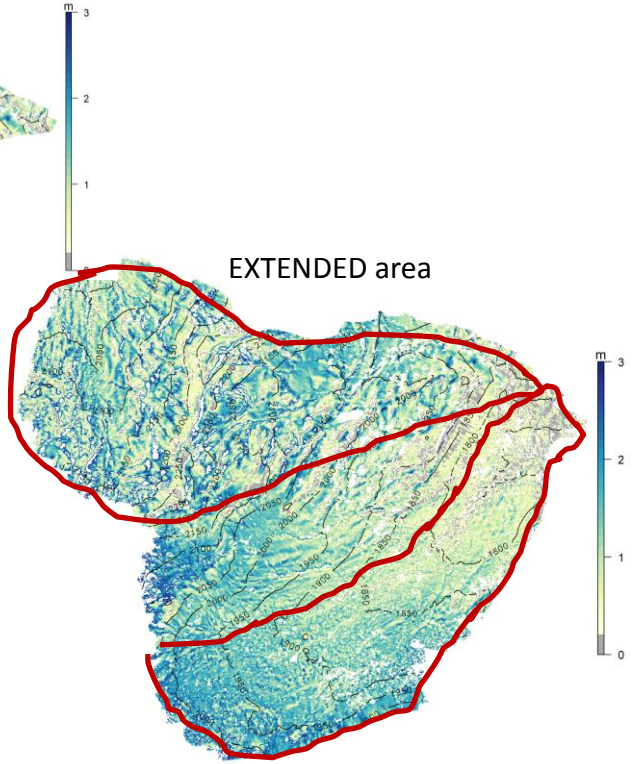


Can we define manually HRU?? (Hydrologic Response Units)

- Are there marked differences in the analysis depending on these limits?

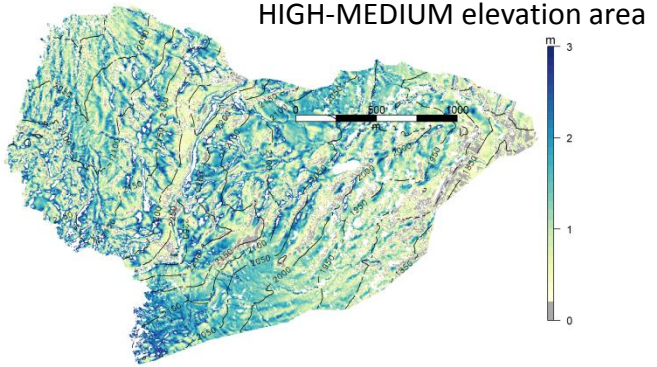


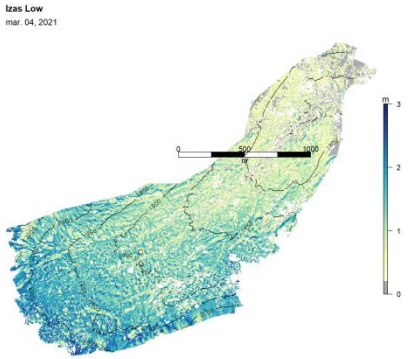
HIGH elevation area



EXTENDED area

HIGH-MEDIUM elevation area





LOW elevation area

Can we define manually HRU?? (Hydrologic Response Units)

			EXTENDED		HIGH		Low		High-Med	
Fechas	MeanSD	SCA	ScaleBraeak	TPI dist	ScaleBraeak	TPI	ScaleBraeak	TPI	Scale break	TPI dist
14/01/2020	1,07	0,94	16,9	20	17,1	20	12,3	12,5	17,8	12
03/02/2020	1,29	0,95	17,3	20	17,6	20	11,6	10	17,5	17,5
24/02/2020	1,15	0,86	16,6	20	17,2	20	11,2	10	17,7	20
11/03/2020	1,52	0,94	20,3	25	21,4	25	11,9	15	20,9	25
24/04/2020	1,19	0,54	18,2	25	18,9	20	11,7	15	18,1	22,5
29/04/2020	1,23	0,63	17,7	25	18	20	11,5	15	17,1	20
03/05/2020	1,12	0,38	18	20	17,6	20	11,3	15	17,4	20
12/05/2020	1,07	0,24	16,5	20	16,1	20				
19/05/2020	1,03	0,22	16,3	20	16,6	25				
26/05/2020	0,78	0,11	15,9	20	16,6	30				
02/06/2020	0,51	0,15	14,8	17,5	15,3	25				
02/02/2021	1,45	0,72	18,1	25	17,6	20	11,8	15	16,75	12,5
04/03/2021	1,29	0,89	16,4	20	17,2	20	12,6	15	17,2	17,5
23/03/2021	1,18	0,79	15,9	20	17	20	12,2	15	16,8	17,5
14/04/2021	1,05	0,45	14,8	20	17,3	20	11,2	12,5	16,4	17,5
04/05/2021	1,03	0,33	16,1	20	16,5	15	11,3	12,5	16,8	15
20/05/2021	0,63	0,42	17,1	20	16,4	15			16,3	17,5
08/06/2021	0,40	0,23	17,3	15	15,4	15				
16/12/2021	1,19	0,93	18	15	18,3	20	14	12,5	18,2	22,5
12/01/2022	1,12	0,81	17,6	15	17,7	20	13,3	12,5	18,2	20
28/01/2022	1,17	0,86	18,7	20	18,4	20	12,6	15	18,4	22,5
18/02/2022	1,11	0,79	17	20	18,1	20	13,5	15	18,5	22,5
17/04/2022	1,20	0,51	16,9	20	17,6	20	12,1	10	17,8	20
16/05/2022	1,06	0,21	16,5	20	15,9	20			15,8	15
01/12/2022	0,45	0,36	12,3	15	12,6	15	10,3	10	13,8	15
13/02/2023	0,98	0,89	14,7	20	15,4	20	12,2	15	15,3	20
16/03/2023	0,81	0,59	14,3	20	15,4	20	11,8	15	15,2	15
28/03/2023	0,74	0,42	14,1	20	14,5	20	11,8	20	14,5	10
20/04/2023	0,74	0,23	14,4	20	14,6	20	11,7	20	14,4	20
02/05/2023	0,55	0,17	14,9	20					15,3	20
		MEAN	16,4533333	19,9166667	16,83793103	20,1724138	11,9857143	13,9285714	16,886	18,28

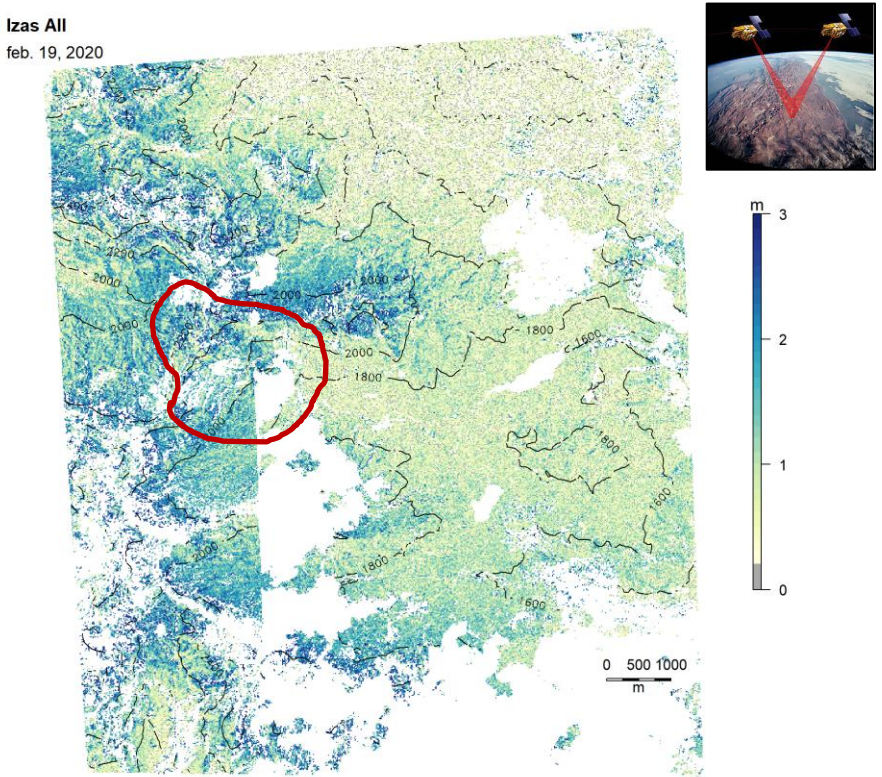
- Scale breaks and the best search distance for the TPI (best correlated topographic variable variable) are similar in all HRUs .
- Equivalent result for 4 snow season
- Higher distances with higher snow accumulation

Can we define manually HRU?? (Hydrologic Response Units)

			EXTENDED		HIGH		Low		High-Med	
Fechas	MeanSD	SCA	ScaleBraeak	PeakDist	ScaleBraeak	PeakDist	ScaleBraeak	PeakDist	Scale break	PeakDist
14/01/2020	1,07	0,94	16,9	14,95	17,1	16,8	12,3	11,35	17,8	16,525
03/02/2020	1,29	0,95	17,3	18,55	17,6	16,05	11,6	12,2	17,5	19,325
24/02/2020	1,15	0,86	16,6	18,15	17,2	21,025	11,2	12,95	17,7	18,55
11/03/2020	1,52	0,94	20,3	17,35	21,4	19,9	11,9	12,7	20,9	17,3
24/04/2020	1,19	0,54	18,2	20,3	18,9	20,325	11,7	12,2	18,1	14,7
29/04/2020	1,23	0,63	17,7	19,5	18	18,45	11,5	12,1	17,1	15,3
03/05/2020	1,12	0,38	18	15,675	17,6	20,35	11,3	11,8	17,4	16,425
12/05/2020	1,07	0,24	16,5	14,15	16,1	17,775				
19/05/2020	1,03	0,22	16,3	18,2	16,6	13,375				
26/05/2020	0,78	0,11	15,9	20	16,6	20,35				
02/06/2020	0,51	0,15	14,8	17,9	15,3	11,175				
02/02/2021	1,45	0,72	18,1	22,3	17,6	21,05	11,8	11,7	16,75	15,2
04/03/2021	1,29	0,89	16,4	15,85	17,2	16,45	12,6	12,8	17,2	16,125
23/03/2021	1,18	0,79	15,9	17,175	17	19,55	12,2	12,3	16,8	16,685
14/04/2021	1,05	0,45	14,8	14,2	17,3	19,55	11,2	12,3	16,4	14,55
04/05/2021	1,03	0,33	16,1	14,3	16,5	14,95	11,3	13,25	16,8	15,325
20/05/2021	0,63	0,42	17,1	12,6	16,4	11,4			16,3	16,125
08/06/2021	0,40	0,23	17,3	11,4	15,4	9,225				
16/12/2021	1,19	0,93	18	19,275	18,3	21,7	14	13,8	18,2	19,075
12/01/2022	1,12	0,81	17,6	15,8	17,7	17,725	13,3	13,925	18,2	16,4
28/01/2022	1,17	0,86	18,7	16,35	18,4	16,875	12,6	12,475	18,4	16,45
18/02/2022	1,11	0,79	17	16,95	18,1	19,525	13,5	13,3	18,5	18,975
17/04/2022	1,20	0,51	16,9	18,975	17,6	17,225	12,1	16,7	17,8	18,1
16/05/2022	1,06	0,21	16,5	24,835	15,9	18,55			15,8	13,475
01/12/2022	0,45	0,36	12,3	19,375	12,6	20,75	10,3	16,5	13,8	19,625
13/02/2023	0,98	0,89	14,7	20,9625	15,4	22,8	12,2	16,85	15,3	22,6
16/03/2023	0,81	0,59	14,3	23,4	15,4	19,45	11,8	16,15	15,2	18,025
28/03/2023	0,74	0,42	14,1	17,525	14,5	18,3	11,8	16,975	14,5	18
20/04/2023	0,74	0,23	14,4	16,3	14,6	15,45	11,7	14,375	14,4	16,85
02/05/2023	0,55	0,17	14,9	16,425					15,3	15,05
		MEAN	16,4533333	17,6240833	16,83793103	17,7965517	11,9857143	13,5772727	16,886	16,9904

- Scale break and peak snow accumulation distances are similar in all HRUs
- Equivalent result for 4 snow season
- Higher distances with higher snow depths

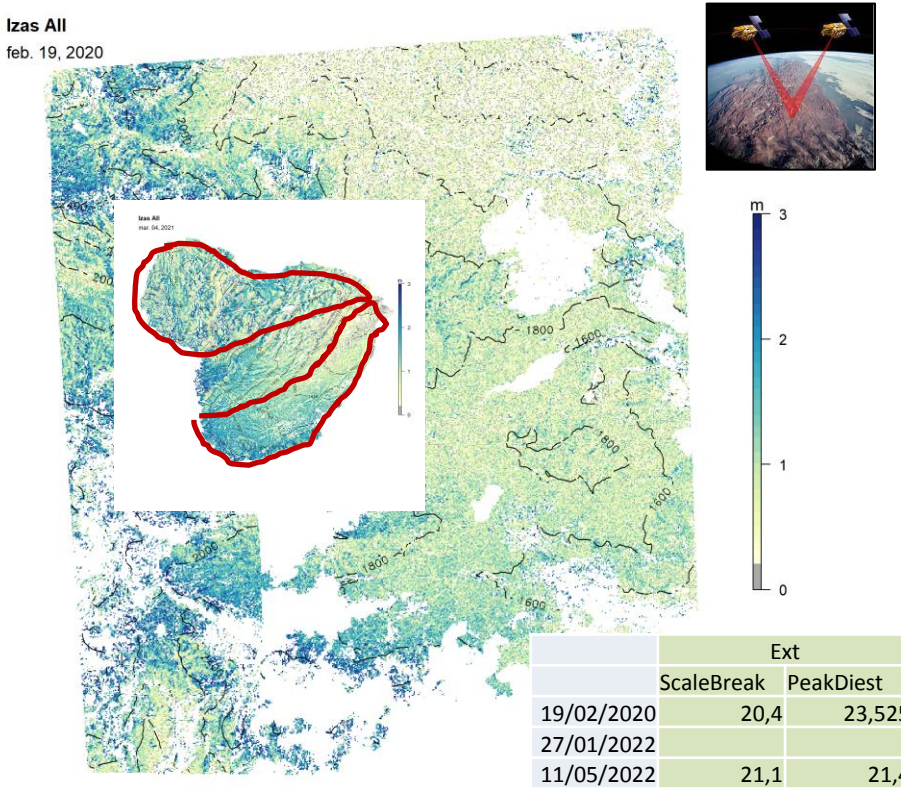
Similar results with differnt observation techniques?



Pleiades acquisitions

	MeanSD	SCA	TPI dist	Scale break	PeakSD-dist
19/02/2020	1,38	0,91	30,00	22,30	21,075
27/01/2022	1,48	0,90	30,00	23,40	24,2
11/05/2022	1,22	0,86	30,00	22,00	20,9
15/02/2023	1,17	0,91	30,00	23,40	21,9
		Mean	**30**	**22,78**	**21,95**

Similar results with differnt observation techniques?



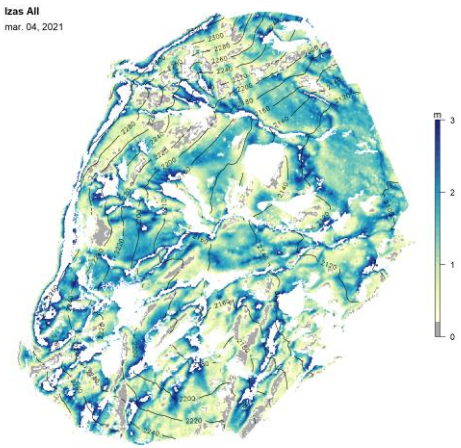
Pleiades acquisitions

	MeanSD	SCA	TPI dist	Scale break	PeakSD-dist
19/02/2020	1,38	0,91	30,00	22,30	21,075
27/01/2022	1,48	0,90	30,00	23,40	24,2
11/05/2022	1,22	0,86	30,00	22,00	20,9
15/02/2023	1,17	0,91	30,00	23,40	21,9
		Mean	**30**	**22,78**	**21,95**

- Scale break, TPI search distance and peak SD distance have similar values.
- Same results if HRU masks are applied to Pleaides snow depth maps

	Ext		High		Low		High-Medium	
	ScaleBreak	PeakDiest	ScaleBreak	PeakDiest	ScaleBreak	PeakDiest	ScaleBreak	PeakDiest
19/02/2020	20,4	23,525	20,8	22,3	19	21,1	20,6	21,8
27/01/2022								
11/05/2022	21,1	21,4	21,1	22,1	18,9	19,9	20,9	20,9
15/02/2023	19,9	20,5	20,5	22,8	18,8	18,8	20,3	19,3
	20,47	**21,81**	**20,80**	**22,40**	**18,90**	**19,93**	**20,60**	**20,67**

Which results are obtained if the TLS mask is applied to UAV acquisitions in different dates?



	Fechas	MeanSD	SCA	TPI dist	Scale break	Peak SD-dist
TLS	22/02/2012	0,949	0,478	**10,000**	**12,600**	**10,500**
	02/04/2012	0,798	0,225	**12,500**	**15,600**	**14,300**
	17/04/2012	0,805	0,607	**15,000**	**13,900**	**9,450**
	17/02/2013	3,183	0,947	**25,000**	**19,400**	**11,600**
	03/04/2013	3,263	0,996	**22,500**	**17,100**	**11,250**
	25/04/2013	2,687	0,913	**22,500**	**17,000**	**11,350**
	06/06/2013	2,453	0,797	**22,500**	**16,800**	**11,225**
UAV	14/01/2020	1,207	0,964	**15,000**	**11,000**	**12,200**
	03/02/2020	1,456	0,943	**15,000**	**10,700**	**14,075**
	11/03/2020	1,766	0,938	**17,500**	**14,500**	**12,725**
	20/05/2020	1,030	0,172	**12,500**	**12,200**	**9,825**
	02/02/2021	1,495	0,787	**17,500**	**10,200**	**13,850**
	04/03/2021	1,488	0,900	**17,500**	**9,900**	**12,400**
	23/03/2021	1,378	0,818	**17,500**	**10,100**	**12,500**
	14/04/2021	1,191	0,611	**12,500**	**9,600**	**13,925**
	02/05/2021	1,005	0,911	**12,500**	**13,200**	**9,850**
	04/05/2021	1,138	0,410	**12,500**	**9,400**	**17,075**
	08/06/2021	0,700	0,025	**17,500**	**10,100**	**8,750**
			Promedio	**16,528**	**12,961**	**12,047**

- Scale breaks, TPI search distance and peak SD distance have similar values
- Scale breaks might be used to validate techniques without contemporary acquisition dates.

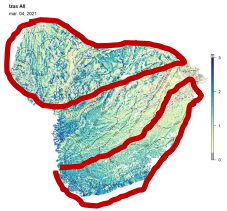
Conclusions:

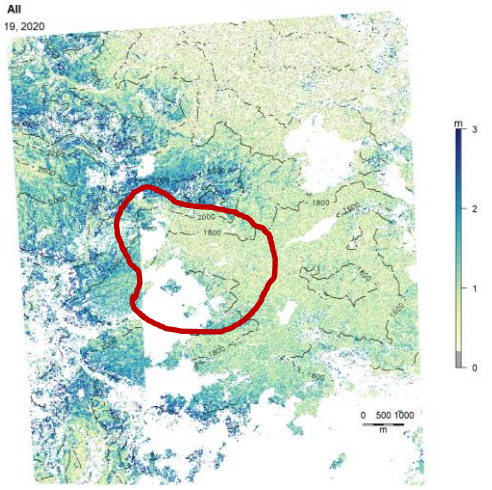
- **Novel snow depth observations** enable to capture **scales** not affordable some years ago.
- **Temporal consistency** of **first scale break** and **fractal dimension** along **10 years** in **small (LiDAR)** and **medium (UAV and Pleiades)** domains.
  - ✓ 25 LiDAR observations along 6 years
  - ✓ 30 UAV observations along 4 years.
  - ✓ 4 Pleiades observations

- **No remarkable directional dependence** observed of these scales breaks in the study area with these technique (same scale breaks).

- Correspondence between the **best TPI search distance the scale break and peak snow accumulation➔** topography controls first scale breaks (observed in different domains).

- **Semivariograms** obtained in **same domain** with distinct techniques must show **same scale breaks➔ Validation of** snow observation **techniques** without contemporary acquisitions.





High temporal consistency

Conclusions:

- **Novel snow depth observations** enable to capture **scales** not affordable some years ago.
- **Temporal consistency** of **first scale break** and **fractal dimension** along **10 years** in **small (LiDAR)** and **medium (UAV and Pleiades)** domains.
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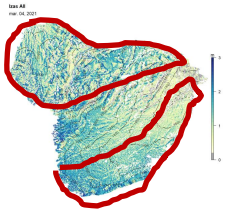

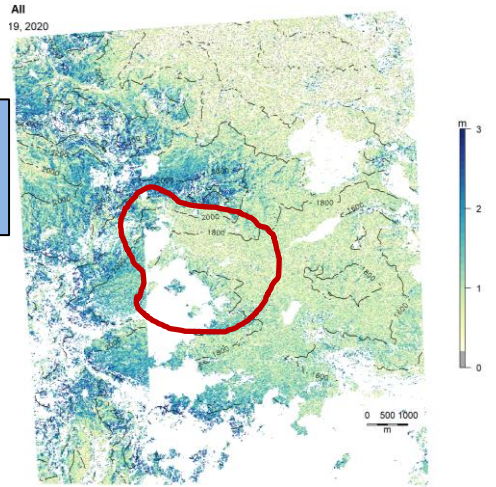

High temporal consistency

- Can we use scale breaks to validate snow observation techniques?
- If the topography is known, can we infer snowpack scale breaks?

- Correspondence between the **best TPI search distance the scale break and peak snow accumulation➔** topography controls first scale breaks (observed in different domains).

- **Semivariograms** obtained in **same domain** with distinct techniques must show **same scale breaks➔ Validation of** snow observation **techniques** without contemporary acquisitions.

A comparison of snow depth scaling patterns from TLS, UAV and Pleiades observations

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