

Scale Breaks in Snow Depth Distribution and Their Topographic Controls: Insights from Remote Sensing and CHM

J. Revuelto¹, M. Courard¹, P. Mendoza², C. Marsh³, I. Goutevin⁴,
F. Rojas-Heredia¹, J.I. López-Moreno¹

¹ Instituto Pirenaico de Ecología, CSIC, Zaragoza, Spain

² Ingeniería civil, Universidad de Chile, Santiago de Chile, Chile

³ Environment and Climate Change, Canada

⁴ Centre d'Etudes de la Neige CNRM, Grenoble, France

⁵ Géographie de l'environnement, CNRS, Toulouse, France



Instituto
Pirenaico
de Ecología
 CSIC



Environment and
Climate Change Canada

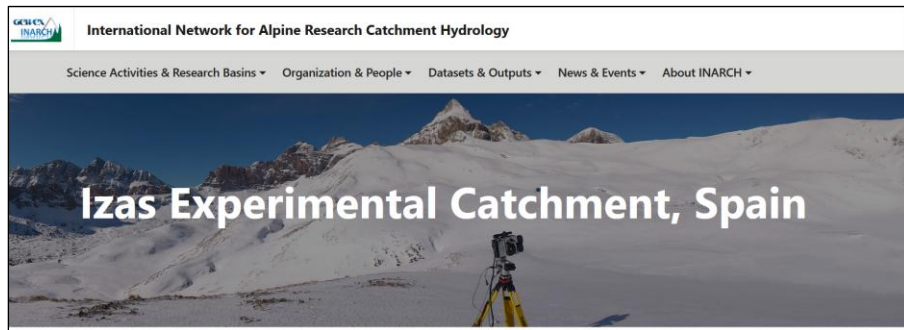


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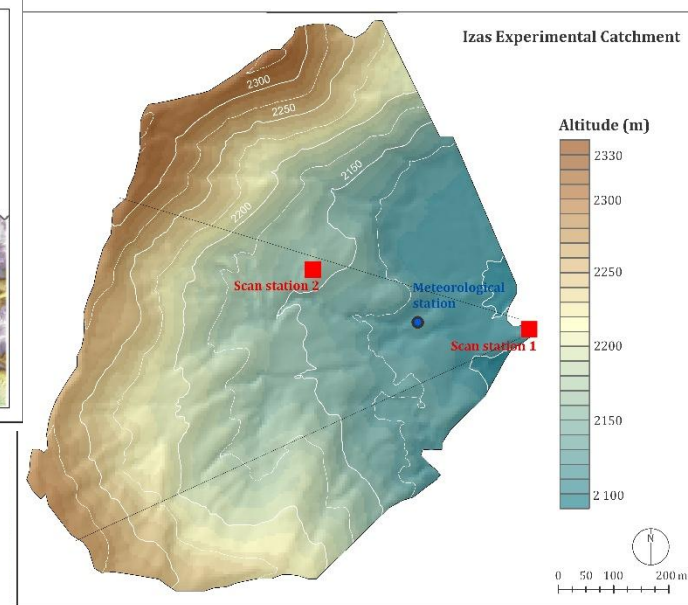
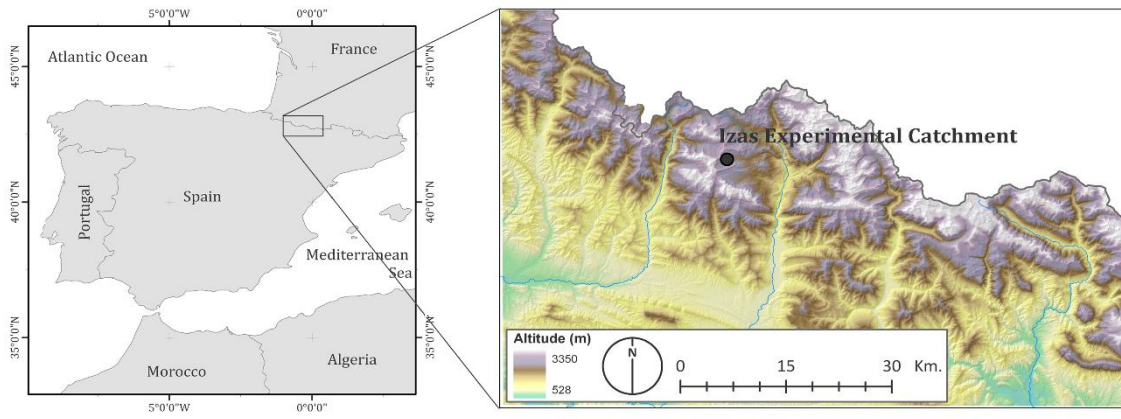
UMR 5602
Géode
géographie de l'environnement

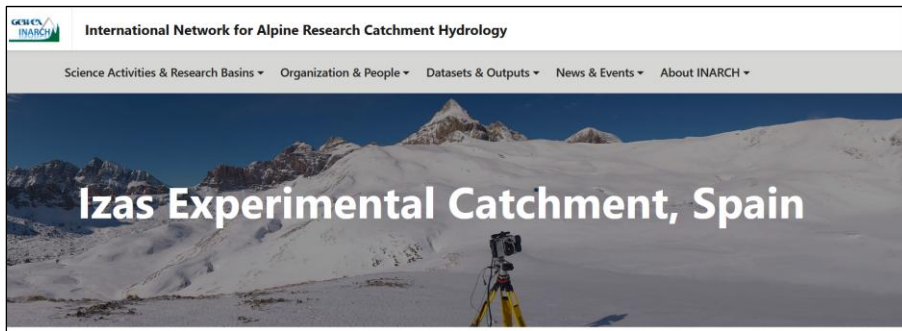




Izas cathcment

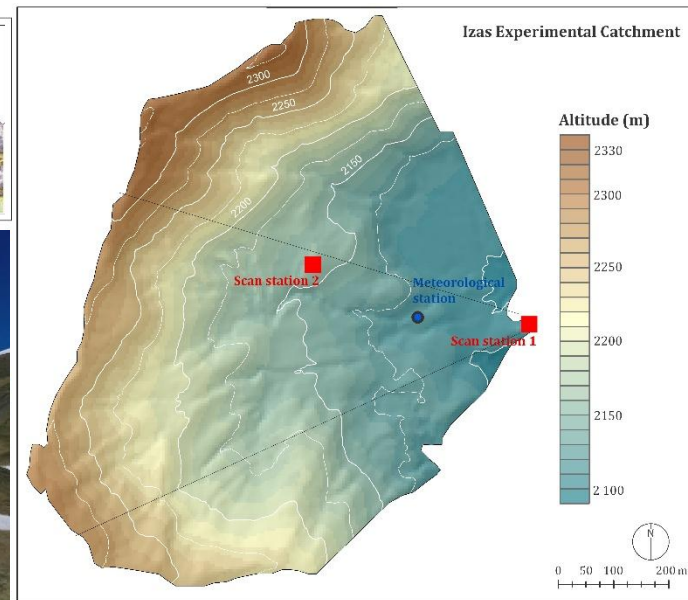
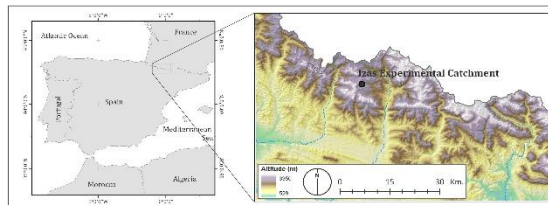
- 55 ha, Altitude: 2000-2300 m

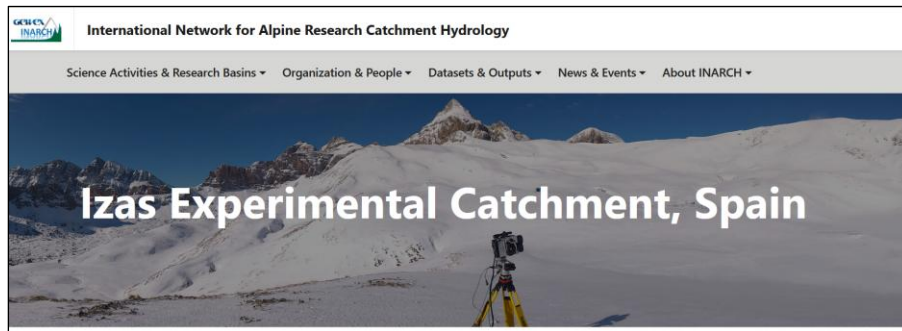




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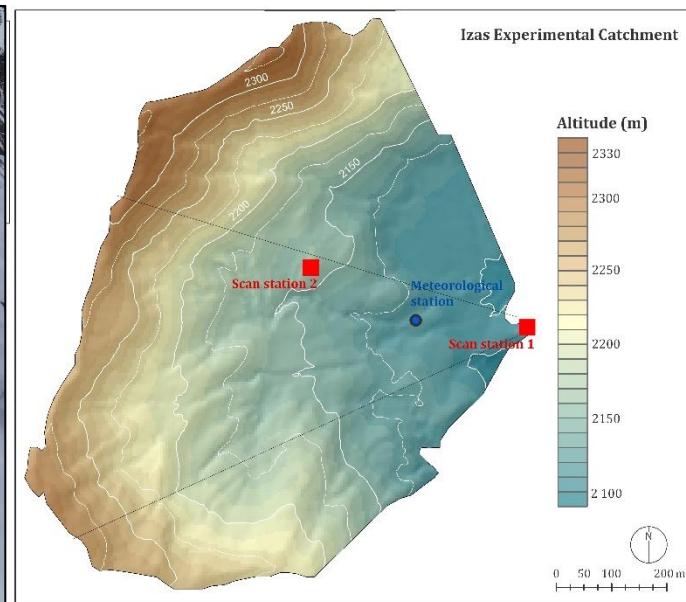
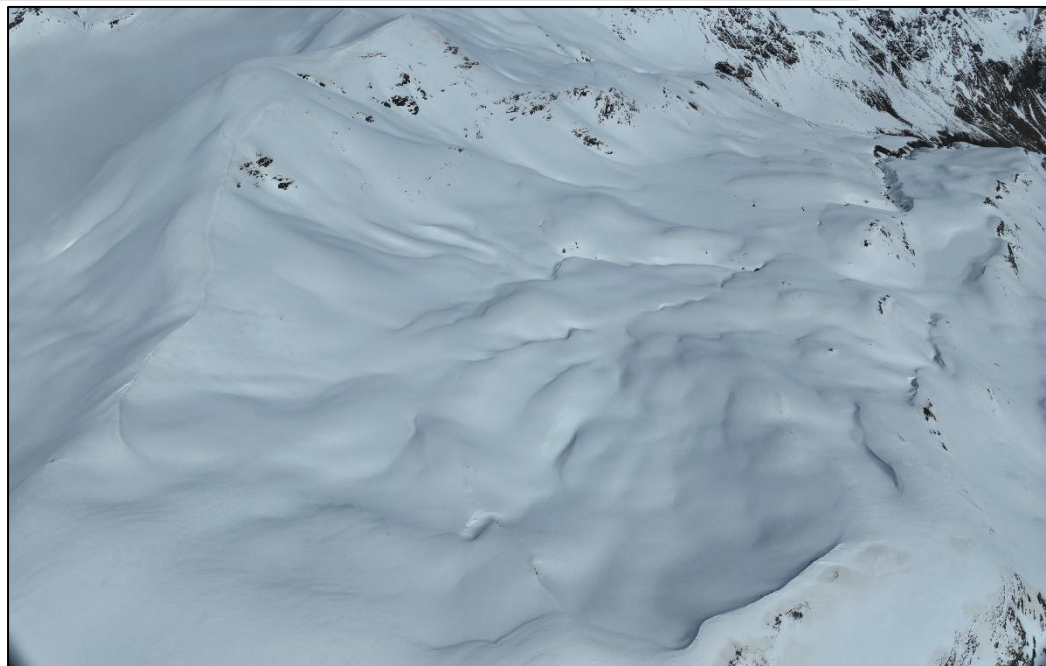
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- Subalpine environment

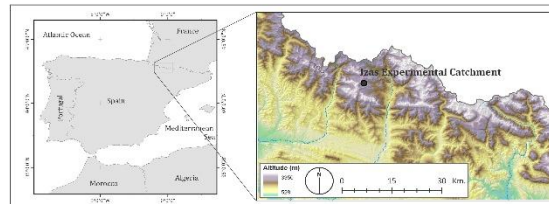




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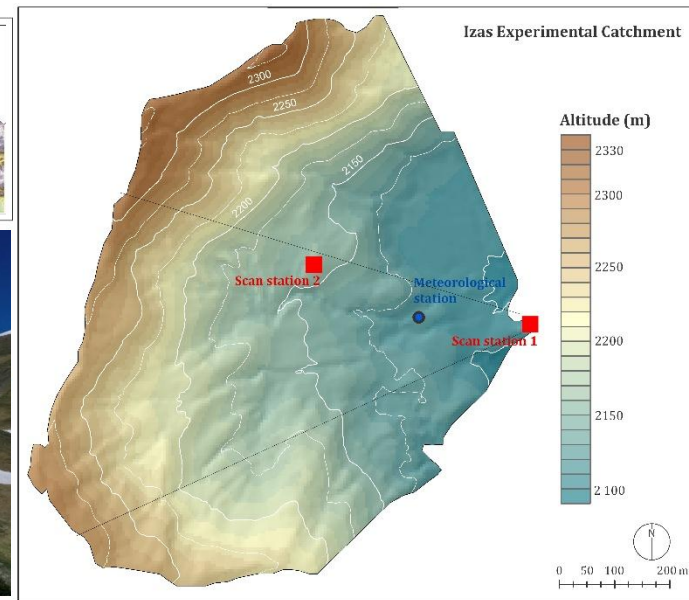
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- Snow covered from December to April-June

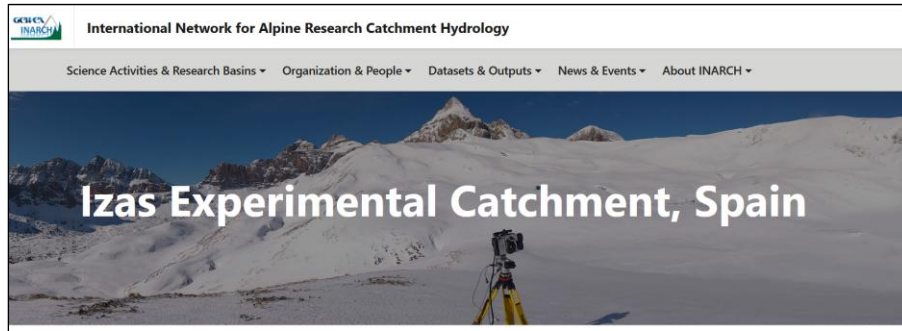




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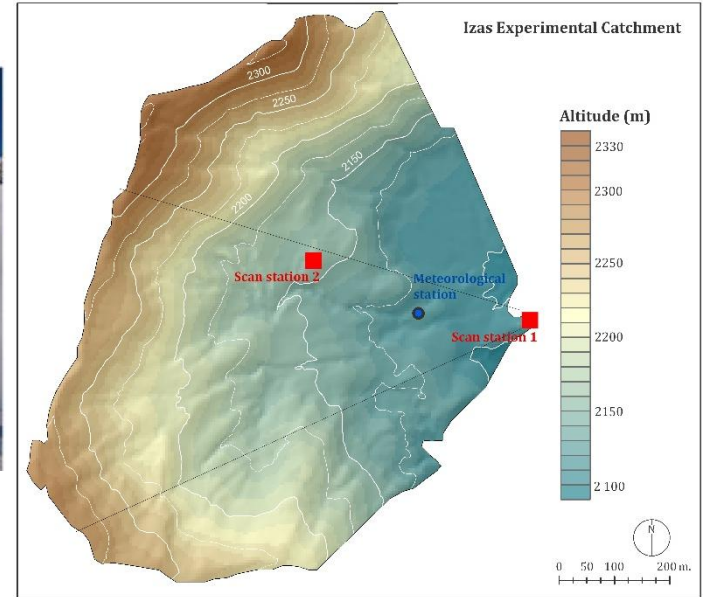
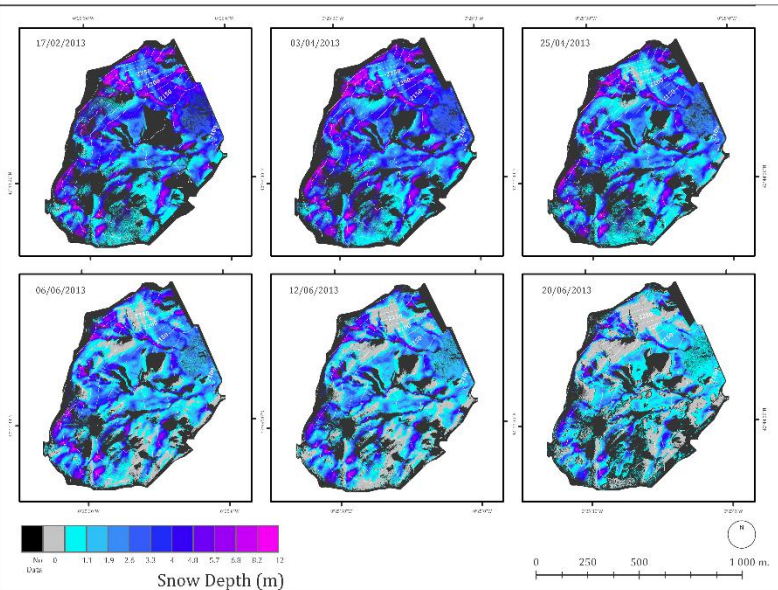
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- Available continuous meteorological observations

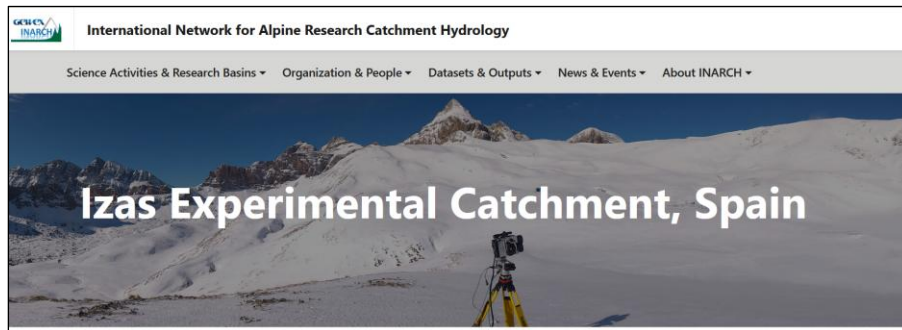




Izas cathcment

- 55 ha, Altitude: 2000-2300 m
- Subalpine environment
- Snow covered from December to April-June
- Available continuous meteorological observations
- LiDAR snow depth maps since 2011





Since 2019-2020 technical improvement: UAV

Water Resources Research

RESEARCH ARTICLE

10.1029/2020WR028980

Special Section:

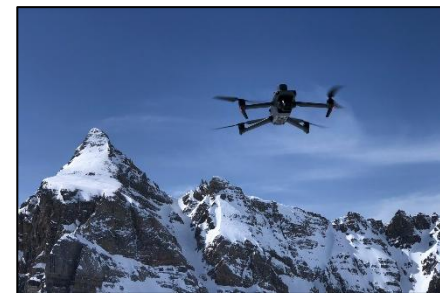
Advances in Remote Sensing, Measurement, and Simulation of Seasonal Snow

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

Jesús Revuelto¹, Juan Ignacio López-Moreno¹, and Esteban Alonso-González¹

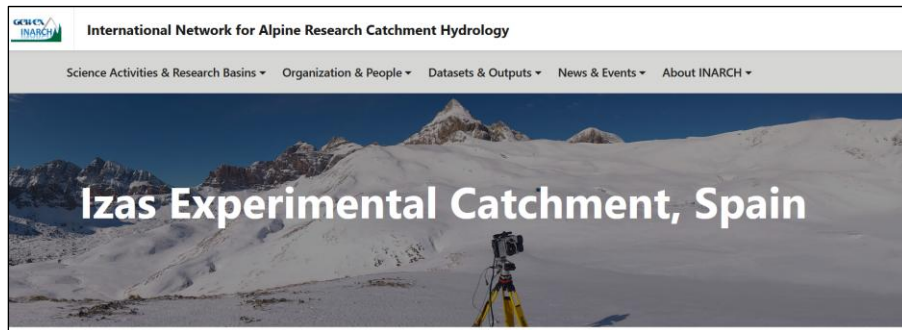
¹Instituto Pirenaico de Ecología, IPE-CSIC, Zaragoza, Spain

Key Points:



UAV acquisitions

Izas catchment + surrounding areas



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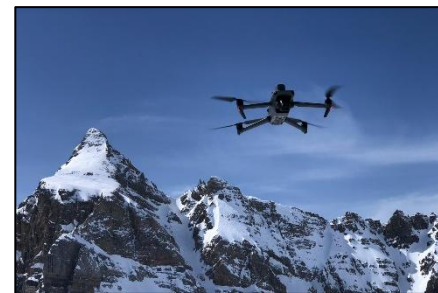
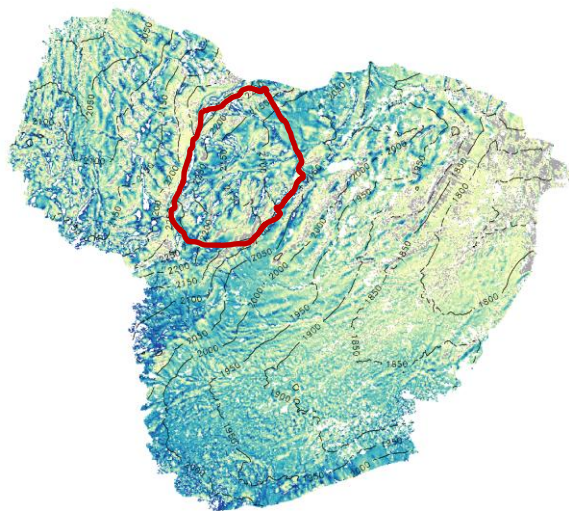
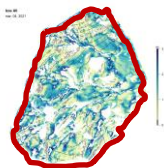
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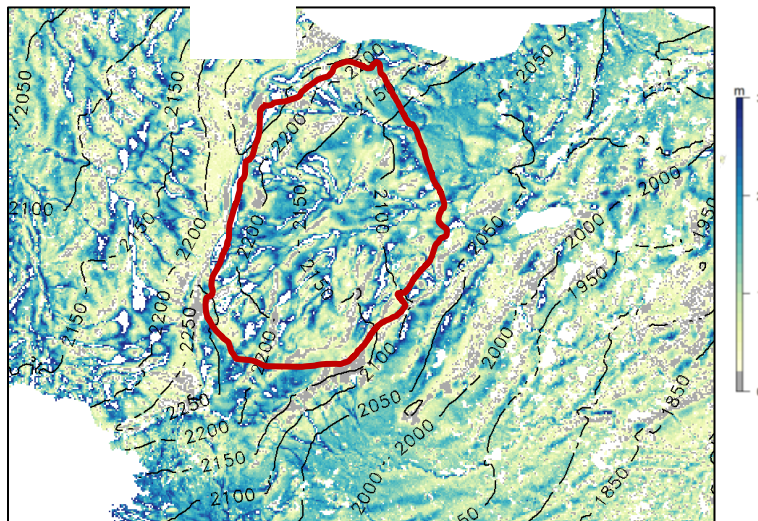
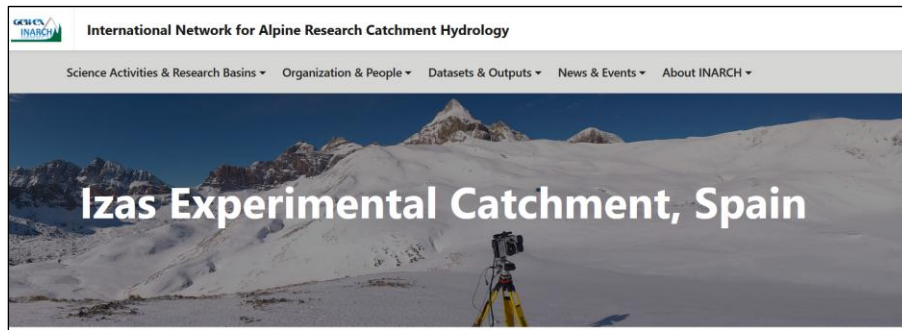
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- 700 ha (before 50 ha)
- 1700-2300 m (before 2000-2300 m)



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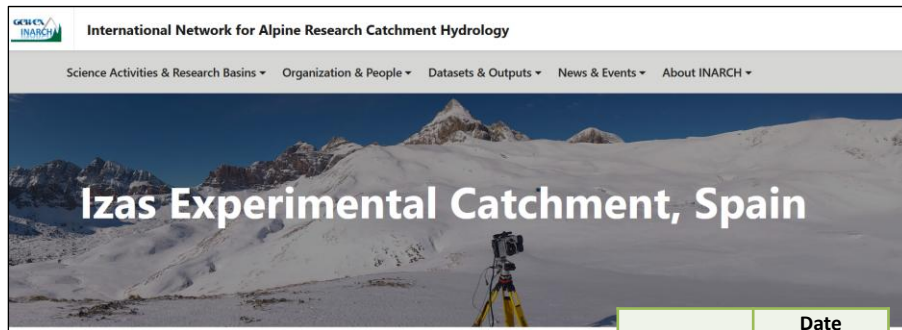
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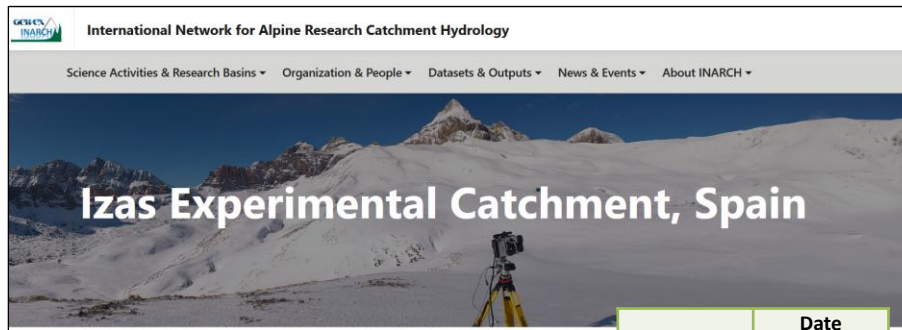
- 700 ha (before 50 ha)
- 1700-2300 m (before 2000-2300 m)
- Wind transport + investigate snow scaling behavior over extended areas



	Date	
2019-2020	14/01/2020	2022-2023
	03/02/2020	
	24/02/2020	
	11/03/2020	
	24/04/2020	
	29/04/2020	
	03/05/2020	2023-2024
	12/05/2020	
	19/05/2020	
	26/05/2020	
2020-2021	02/06/2020	
	02/02/2021	2024-2025
	04/03/2021	
	23/03/2021	
	14/04/2021	
	04/05/2021	
2021-2022	20/05/2021	
	08/06/2021	2025-2026
	16/12/2021	
	12/01/2022	
	28/01/2022	
	18/02/2022	
	17/04/2022	
	16/05/2022	
		03/12/2022
		04/03/2026
		12/03/2026
		24/03/2026
		09/04/2026
		07/05/2026
		13/05/2026

Snow depth observation at 1m spatial resolution

- ✓ **25 LiDAR (TLS)** observations along 6 years (50ha)
- ✓ **49 UAV** observations along 7 years (200 to 700 ha)



	Date		Date
2019-2020	14/01/2020	2022-2023	01/12/2022
	03/02/2020		13/02/2023
	24/02/2020		16/03/2023
	11/03/2020		28/03/2023
	24/04/2020		20/04/2023
	29/04/2020		02/05/2023
	03/05/2020	2023-2024	25/01/2024
	12/05/2020		13/02/2024
	19/05/2020		07/03/2024
	26/05/2020		14/03/2024
2020-2021	02/06/2020		05/04/2024
	02/02/2021		08/05/2024
	04/03/2021	2024-2025	22/05/2024
	23/03/2021		17/03/2025
	14/04/2021		27/03/2025
	04/05/2021		01/04/2025
2021-2022	20/05/2021	2025-2026	08/04/2025
	08/06/2021		24/04/2025
	16/12/2021		03/12/2025
	12/01/2022		04/03/2026
	28/01/2022		12/03/2026
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Snow depth observation at 1m spatial resolution

- ✓ **25 LiDAR (TLS)** observations along 6 years (50ha)
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This **dataset** is suitable for **model validation** and improving the **understanding** of **snow processes**

Exploited here to determine **snow depth distribution scale breaks**:

- Determine its relation with topography
- Explore the capability of CHM model to reproduce the snow distribution scale breaks

Introduction:

- 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

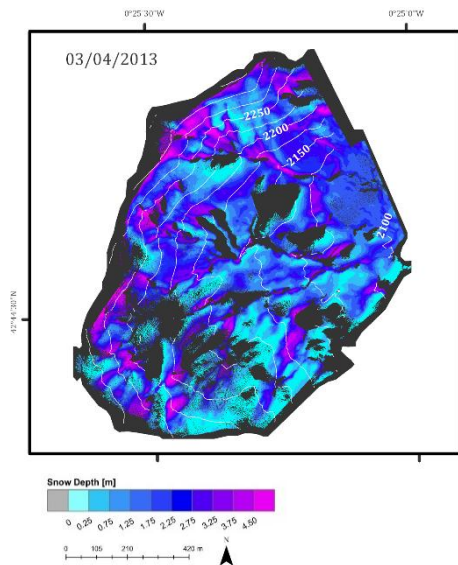
“Measure of an object to fill the space in which resides” (Sun et al., 2006)



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

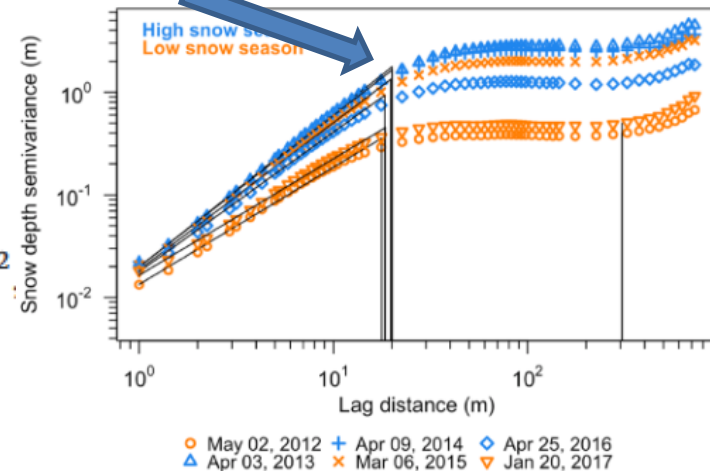
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$$\hat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{(i,j) \in N(h)} (z_j - z_i)^2$$

Scale break



Introduction:

Water Resources Research

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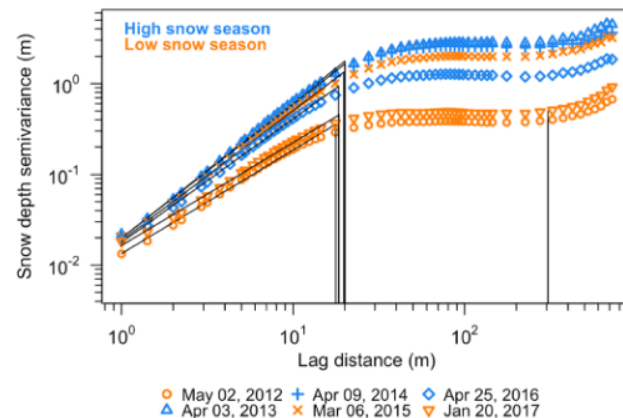
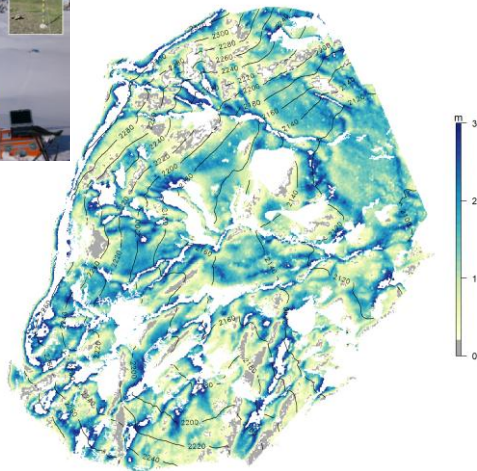
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Special Section:

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. Musselman³ , Jesús Revuelto⁴ , Jeffrey S. Deems⁵ , J. Ignacio López-Moreno⁴ , and James McPhee^{1,2}



- **Consistent short-range fractal behavior and scale breaks in snow depth over 6 years.**
 - Fractal parameter 2.25-2.85
 - Scale breaks 17-24 m

Introduction:

Water Resources Research

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Special Section:

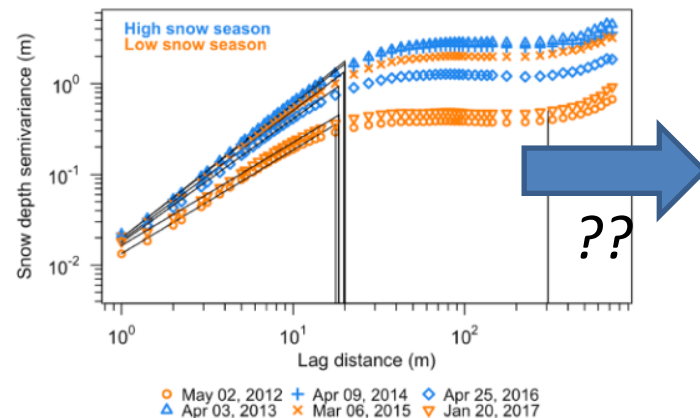
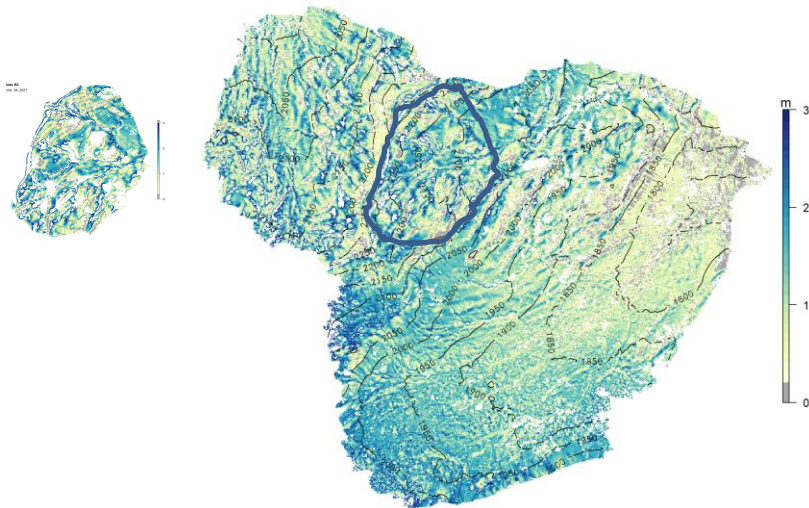
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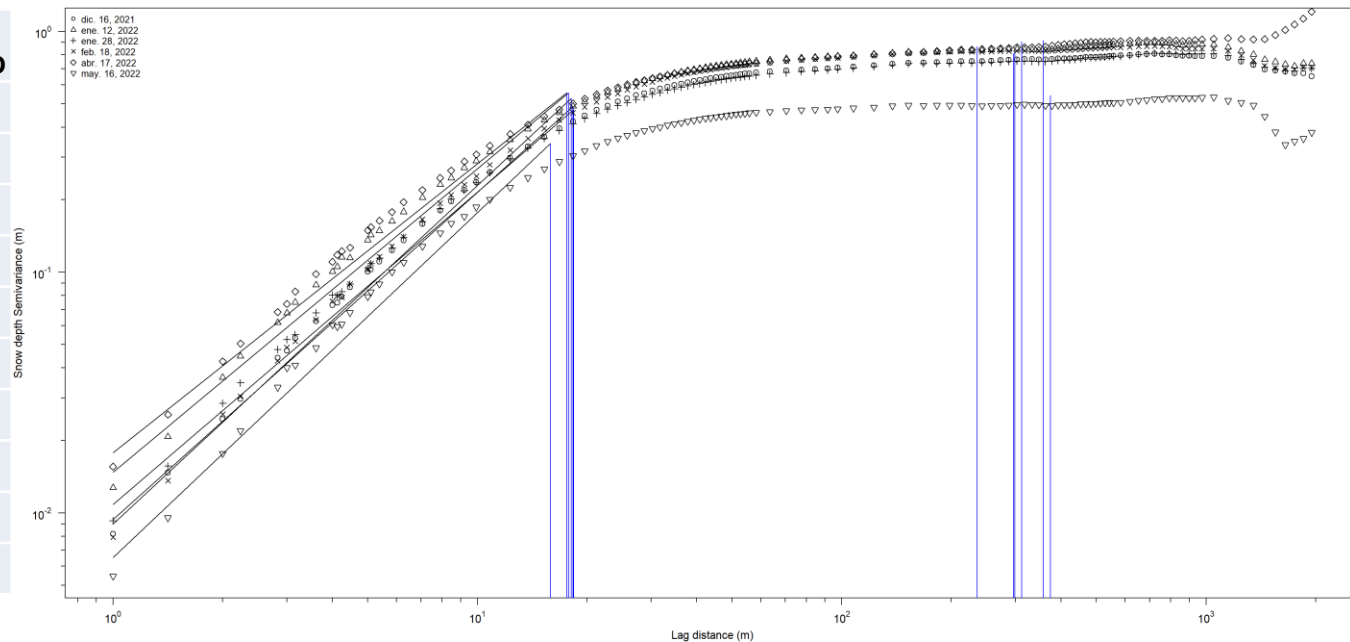
Izias Ali

mar. 04, 2021



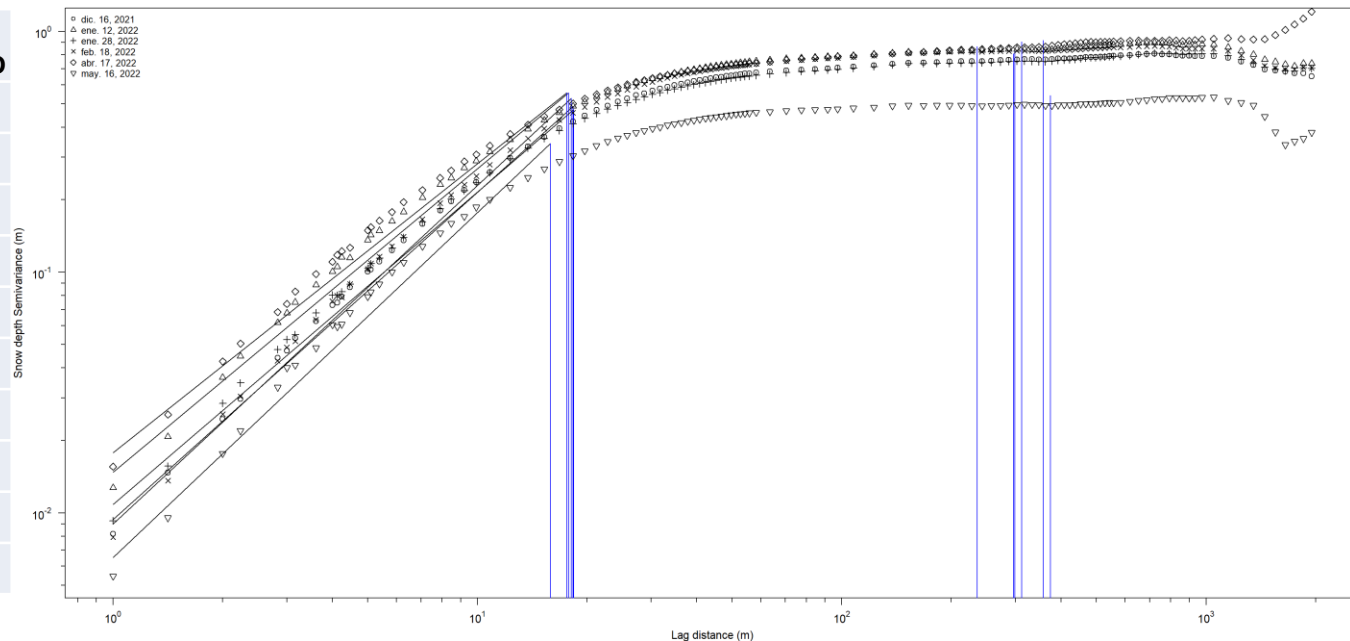
1. First order snow depth distribution scale breaks and its relation with topography

Date	Scale Break (m)	D	Mean SD
14/01/2020	16,9	2,4	1,07
03/02/2020	17,3	2,3	1,29
24/02/2020	17,8	2,3	1,15
11/03/2020	20,3	2,4	1,52
24/04/2020	18,2	2,3	1,19
29/04/2020	17,7	2,3	1,23
03/05/2020	18	2,3	1,12
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- Relate **scale break distances** with **topography**
- “Benchmarking”: Are the results consistent across **different techniques (obs. sim.)**?

1. First order snow depth distribution scale breaks and its relation with topography

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

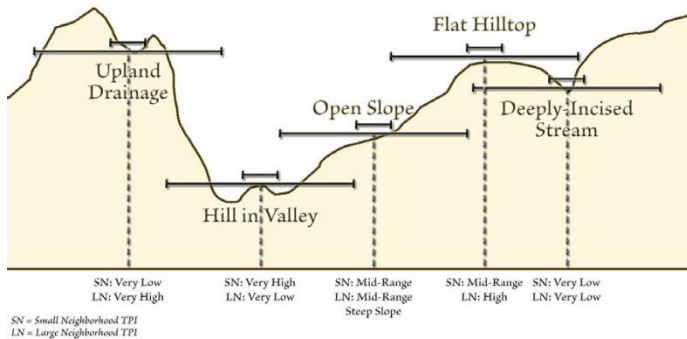
Pearson correlation: topographic variables vs snow depth

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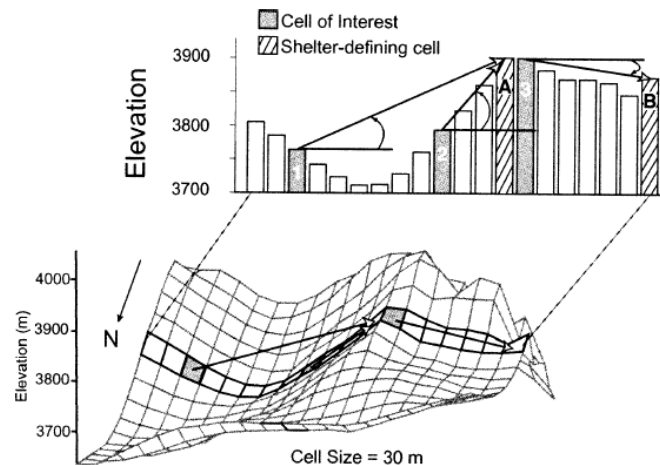
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- *Topographic Position Index (TPI, Weiss, 2001)*



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

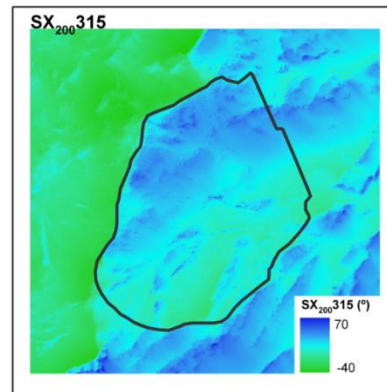
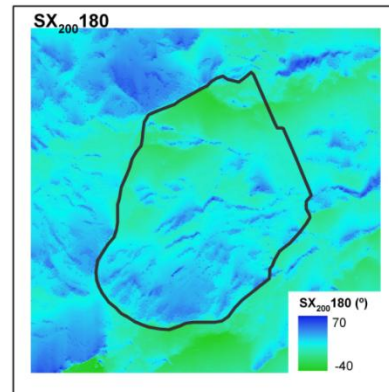
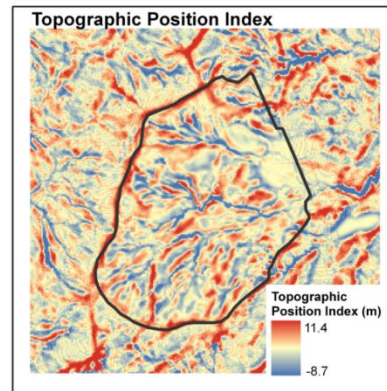
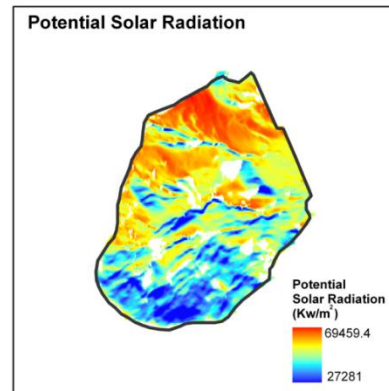
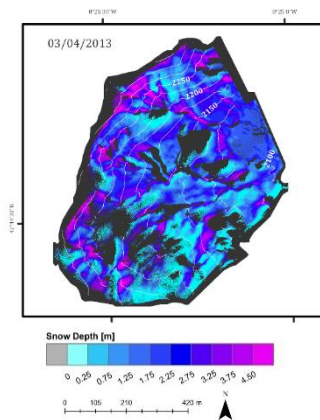


Impact of search distances and/or directions

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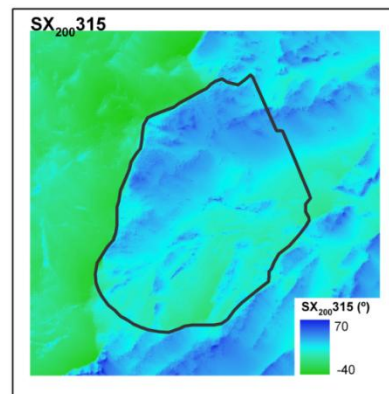
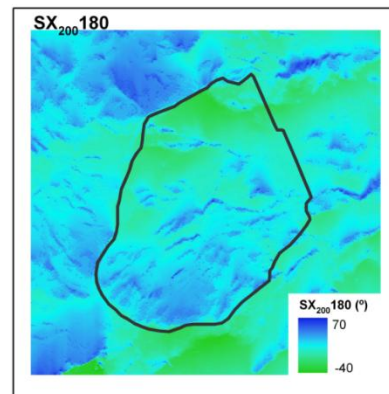
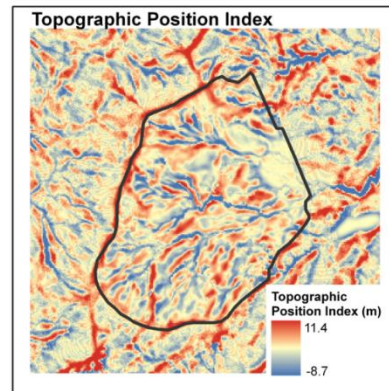
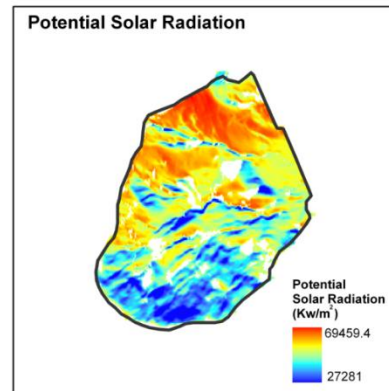
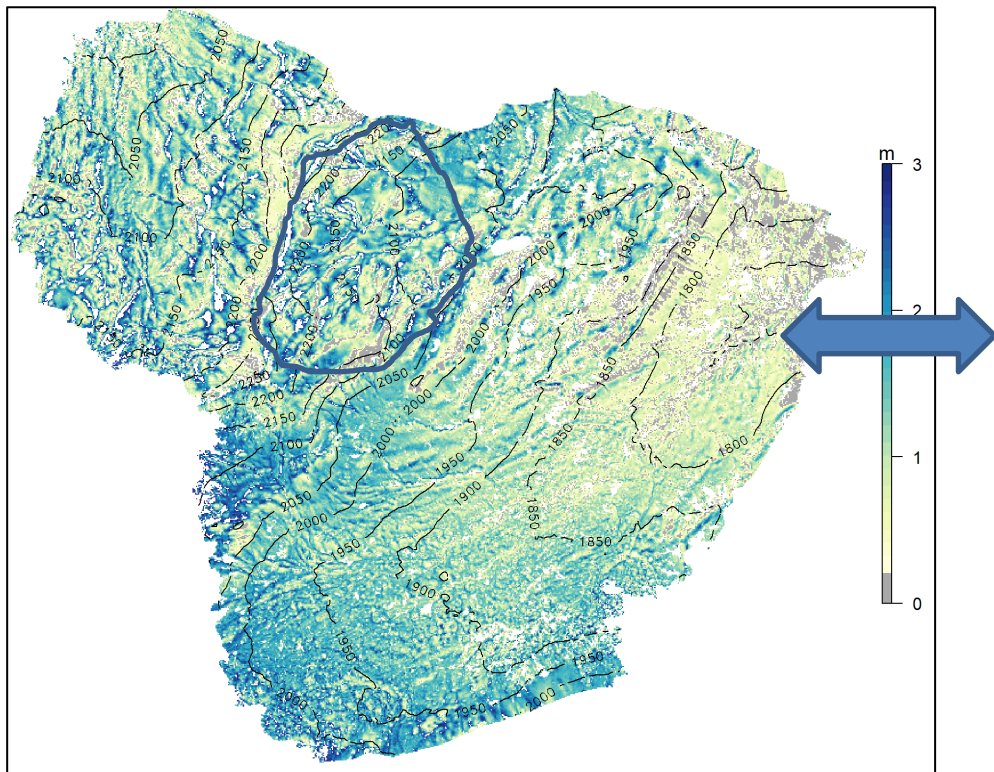
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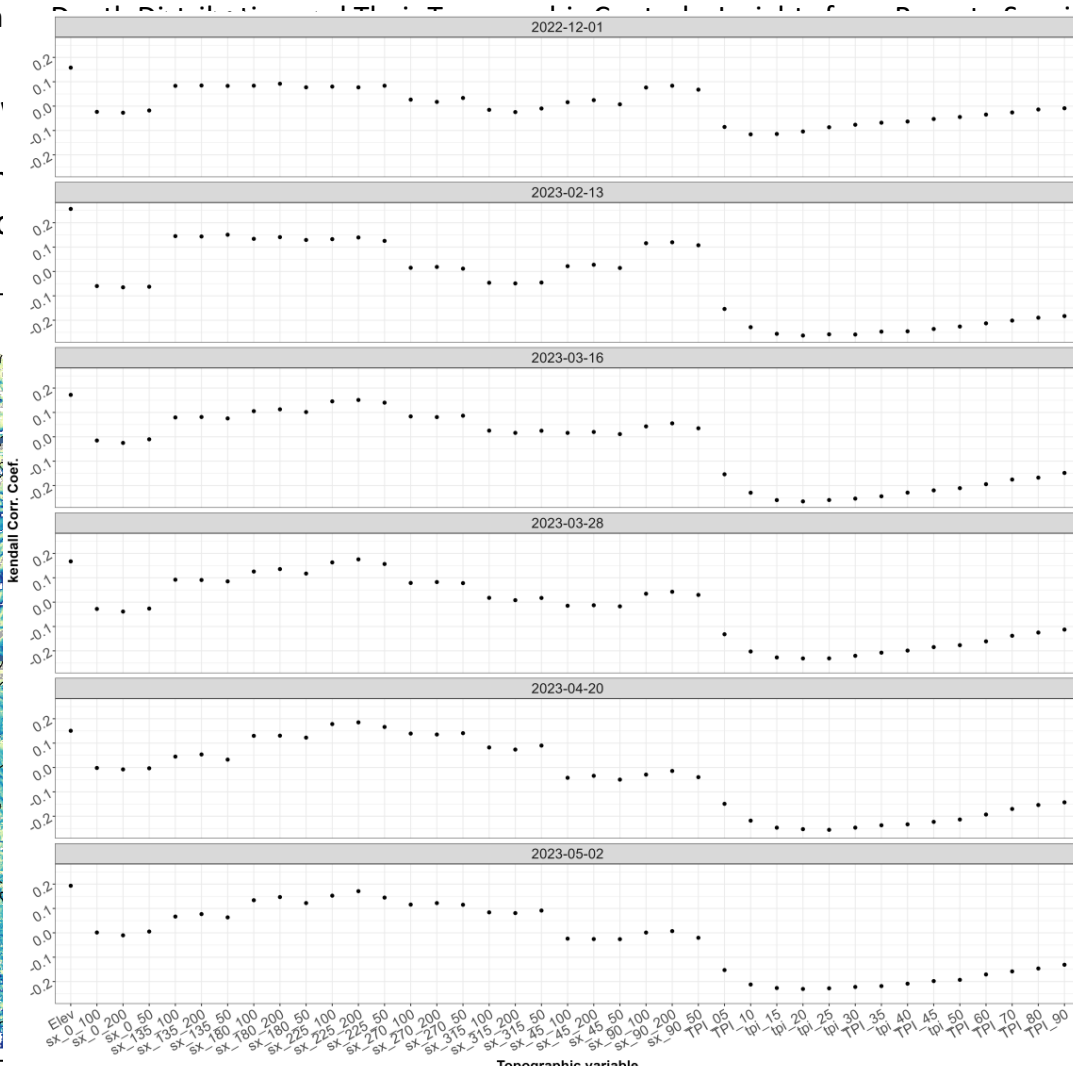
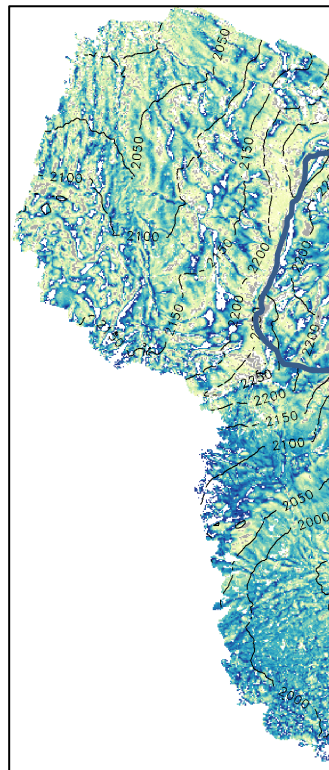
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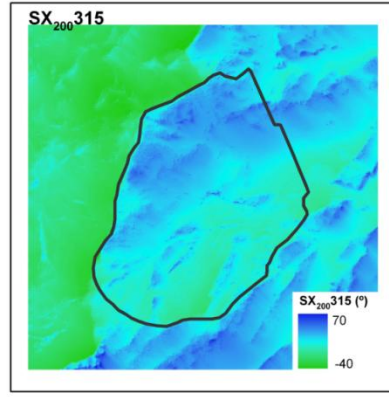
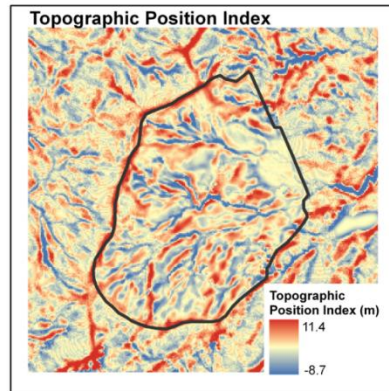


g and CHM

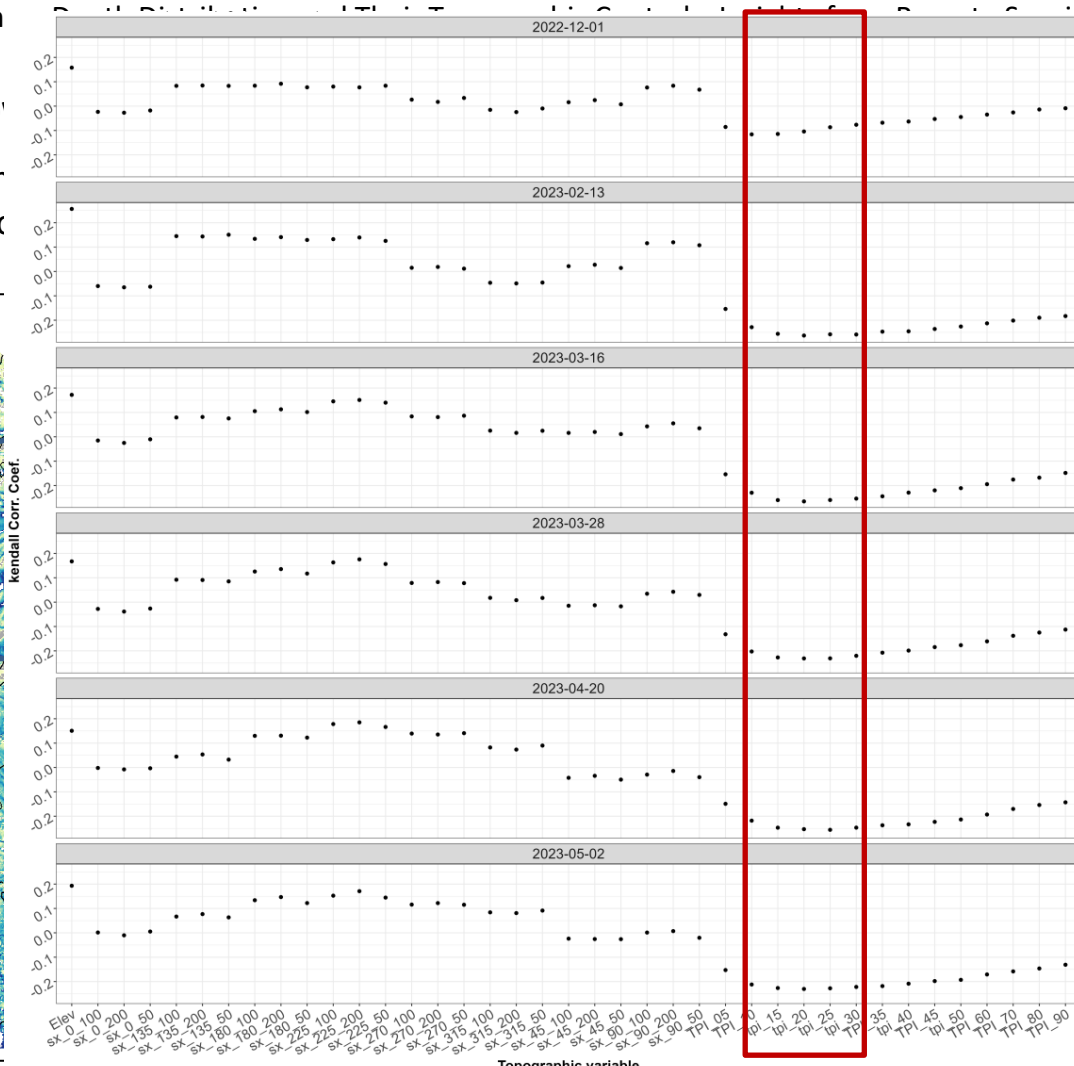
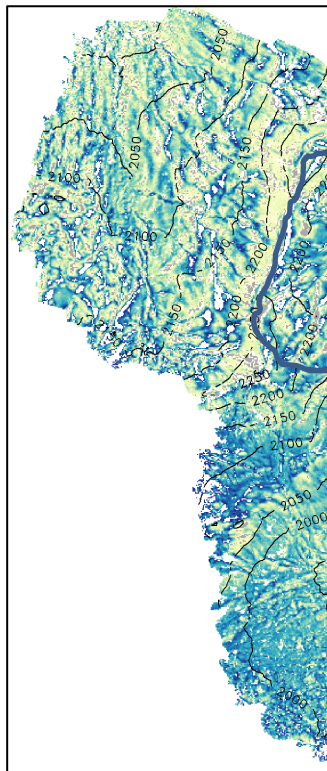
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diation
59.4
81

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0

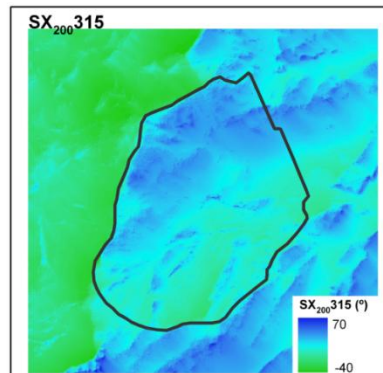
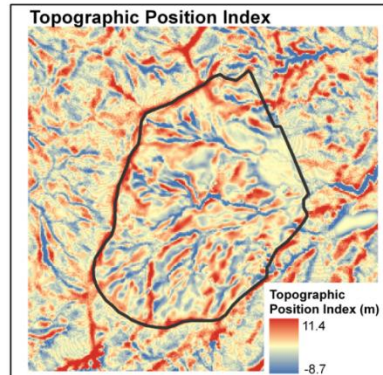


a) Is there any relationship between the variables?
Pearson correlation coefficient



g and CHM

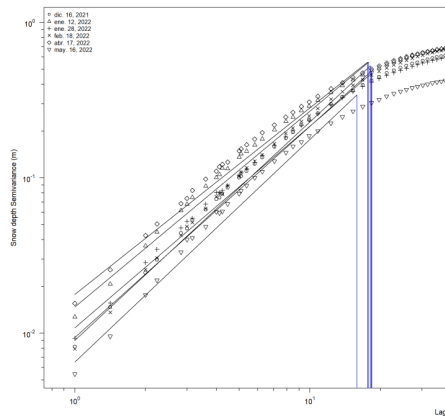
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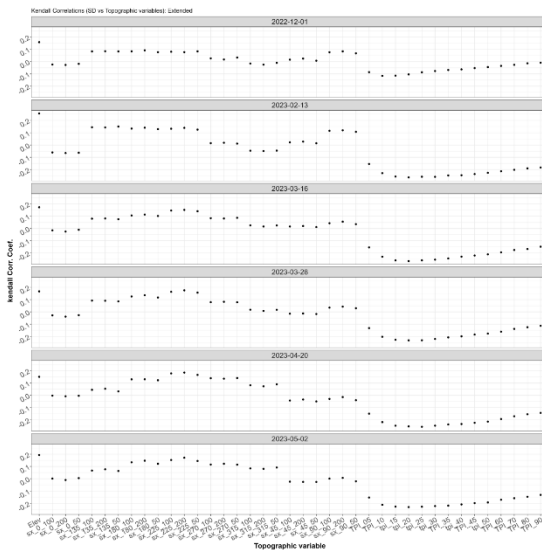
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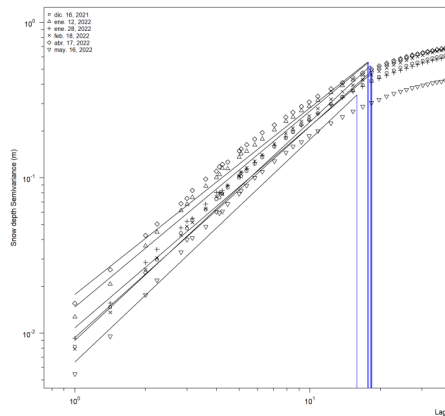
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24/02/2020	17,8	20	1,15	0,86
11/03/2020	20,3	25	1,52	0,94
24/04/2020	18,2	22,5	1,19	0,54
29/04/2020	17,7	20	1,23	0,63
03/05/2020	18	17,5	1,12	0,38
12/05/2020	16,5	17,5	1,07	0,24
19/05/2020	16,3	20	1,03	0,22
26/05/2020	15,9	20	0,78	0,11



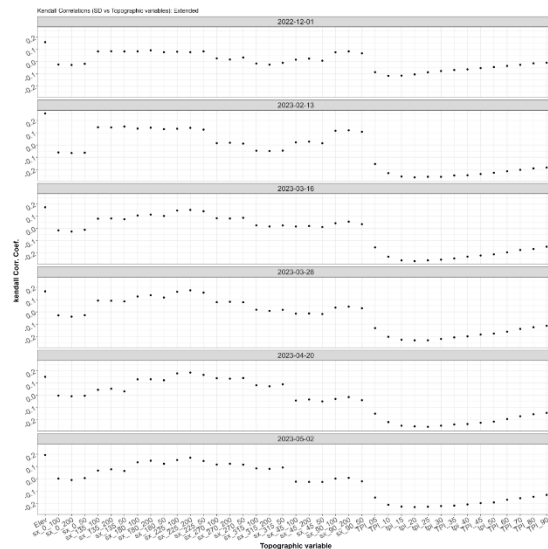
1. First order snow depth distribution scale breaks and its relation with topography

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

Pearson correlation: topographic variables vs snow depth



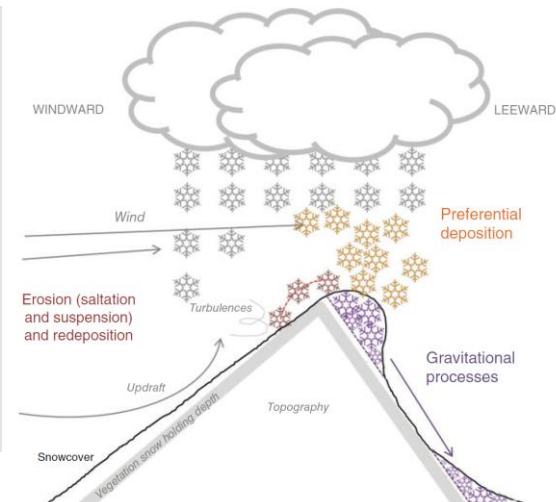
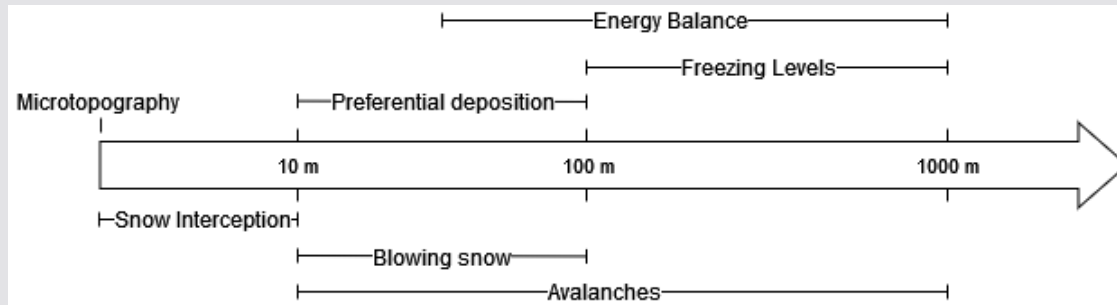
Date	Scale Break (m)	TPI search distance (m)	Mean SD (m)	SCA_(%)
14/01/2020	16,9	15	1,07	0,94
03/02/2020	17,3	17,5	1,29	0,95
24/02/2020	17,8	20	1,15	0,86
11/03/2020	20,3	25	1,52	0,94
24/04/2020	18,2	22,5	1,19	0,54
29/04/2020	17,7	20	1,23	0,63
03/05/2020	18	17,5	1,12	0,38
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Correspondence between the optimal TPI search distance and scale breaks suggesting that topography controls scale breaks and snow accumulation patterns.

2. Can the observed scale breaks be simulated through wind transport and mass-movement processes?

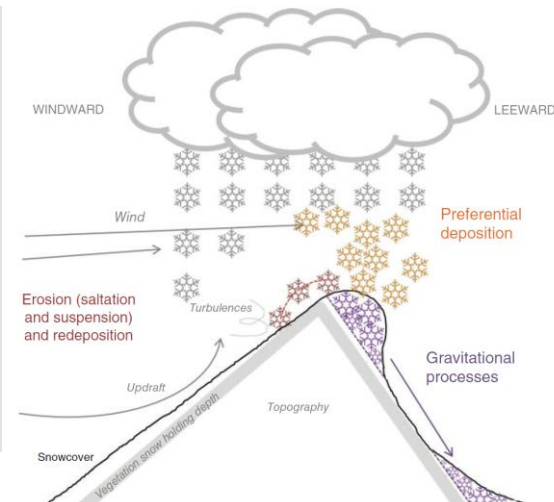
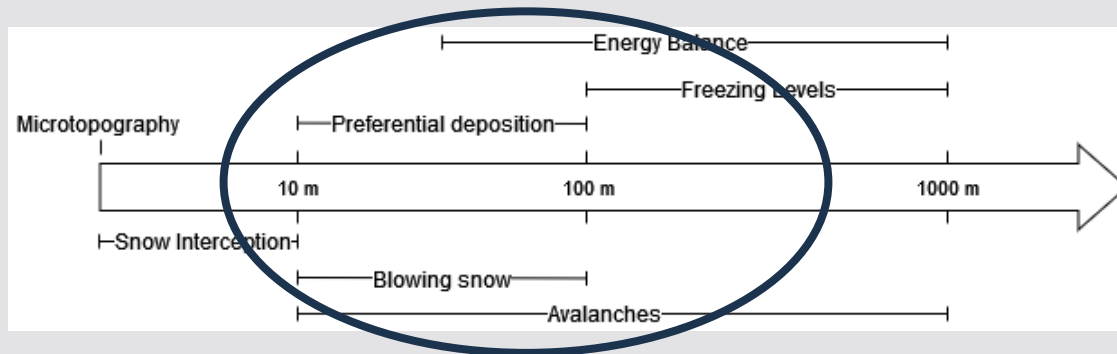
- Snow **spatial variability controlled** by diverse processes at different scales.



2. Can the observed scale breaks be simulated through wind transport and mass-movement processes?

➤ CHM simulations ➔ lateral snow transport

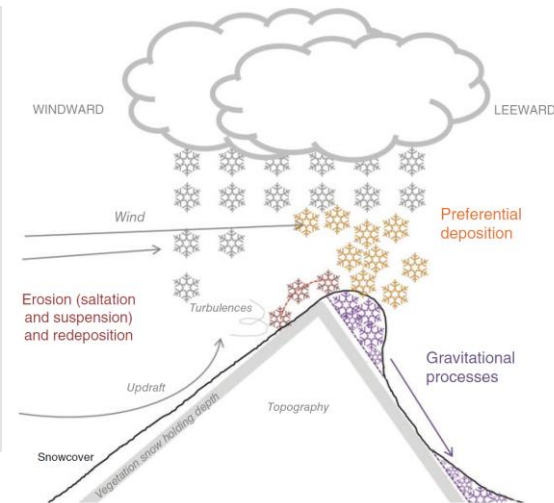
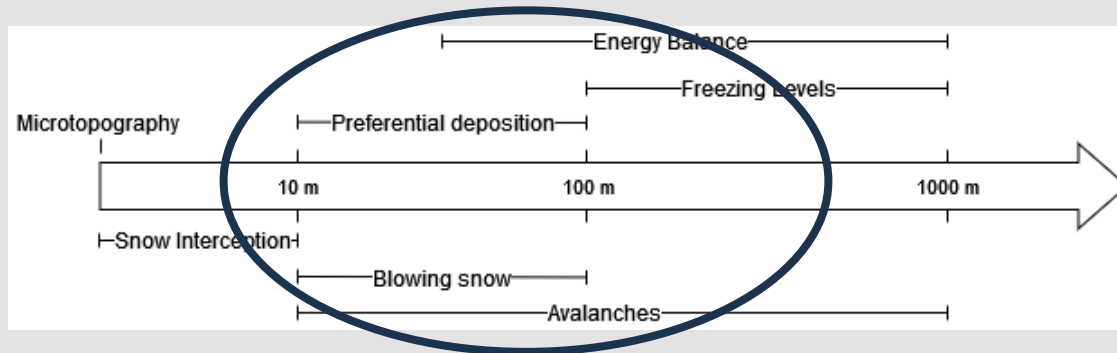
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2. Can the observed scale breaks be simulated through wind transport and mass-movement processes?

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- Snow **spatial variability controlled** by diverse processes at different scales.



Scaling properties of snow depth over longer distances:

- Relate **scale break distances** with **topography**
- “Benchmarking”: Are the results consistent across **different techniques (obs. sim.)**?

2. Can the observed scale breaks be simulated through wind transport and mass-movement processes?

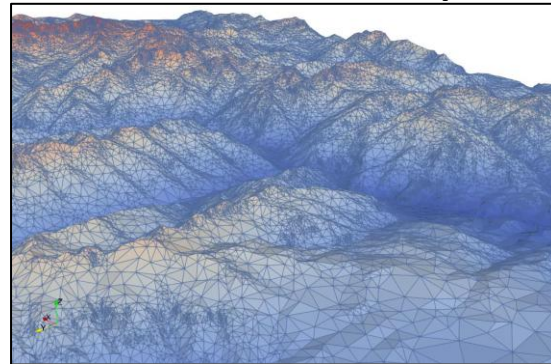
➤ CHM simulations → lateral snow transport

Meteorological forcings

- AROME (1 h, 1.3 km) 2019-2025
- Station-based correction: temperature, precipitation, wind speed, incoming shortwave radiation.

Canadian Hydrological Model (CHM; Marsh et al., 2020)

- Modular: activate/deactivate processes
- Spatially distributed: unstructured triangular meshes
- Downscaling of forcings: orographic lapse rates + Windmapper (Marsh et al., 2023)
- Snow processes: energy and mass balance FSM2 (Essery et al., 2025), avalanche SnowSlide (Bernhardt and Schultz, 2010), blowing snow PBSM3D (Marsh et al., 2020)

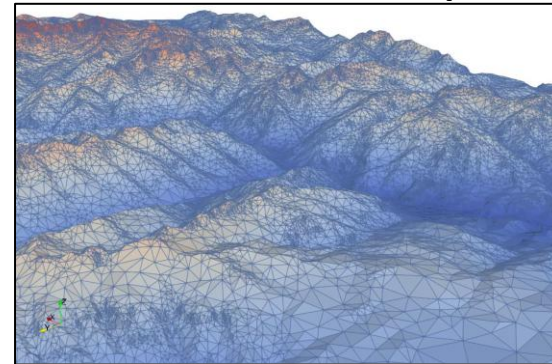


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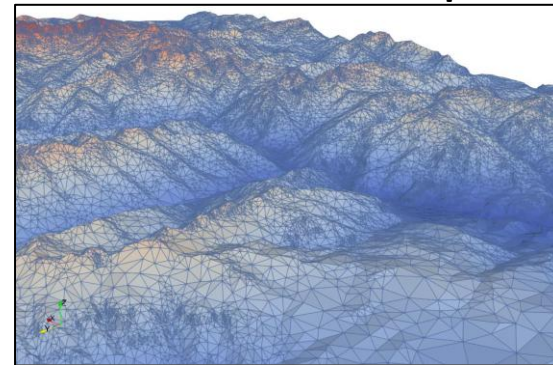
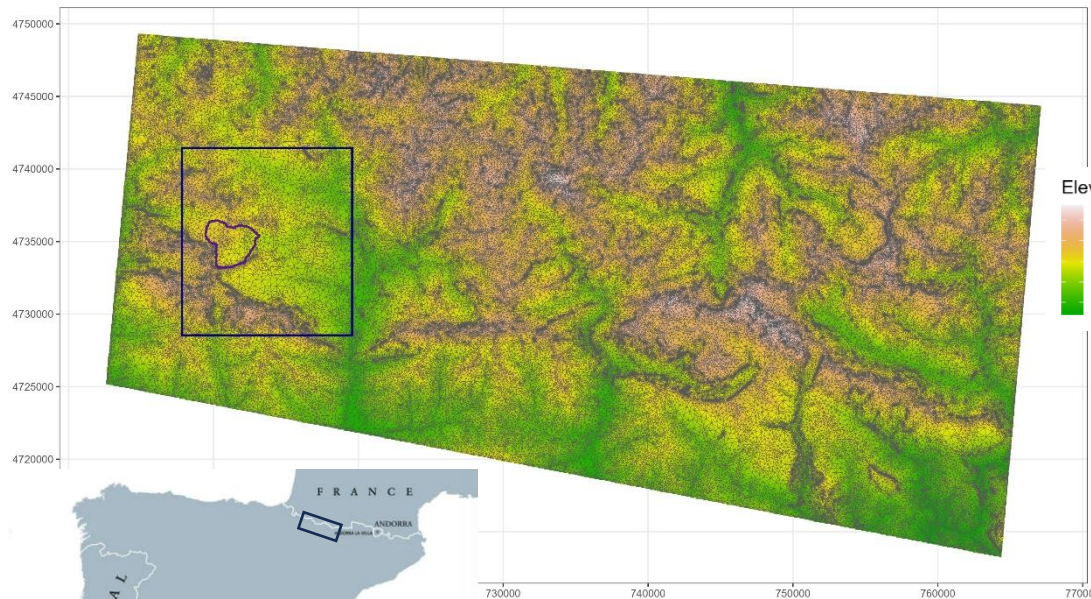
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1 – Catchment	High Resolution (HR)	7.8	120	11
2 – Valley	Medium Resolution (HR)	150	700	26.5
3 - Mountain range	Low Resolution (HR)	1 750	5 330	73

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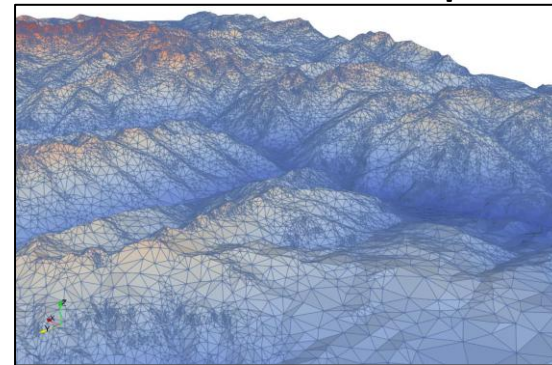
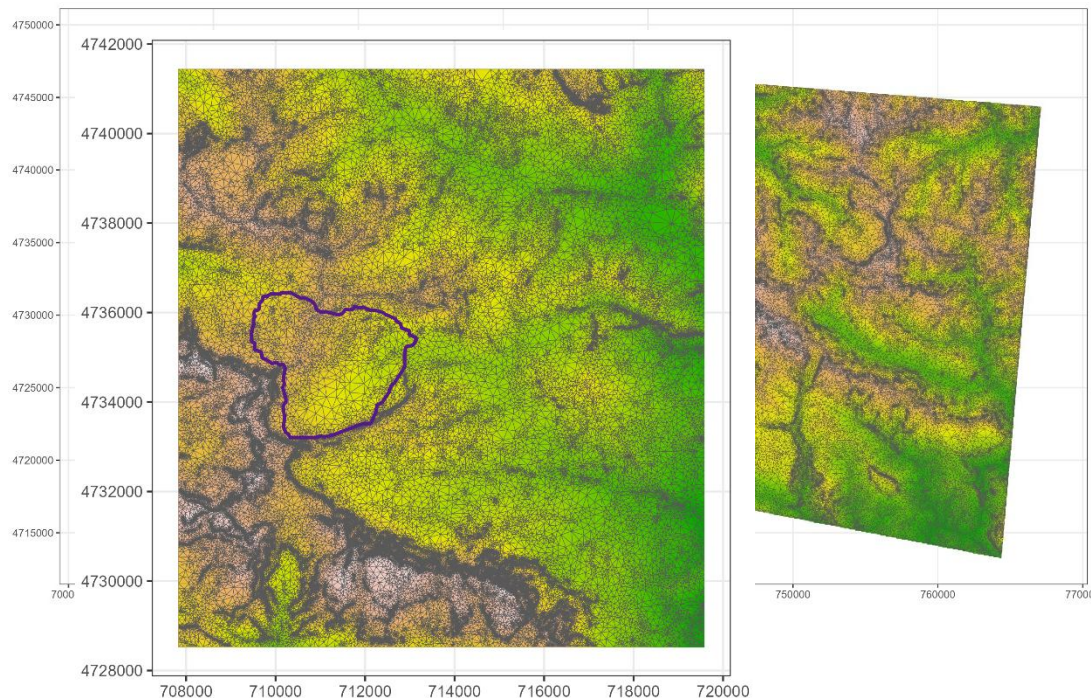


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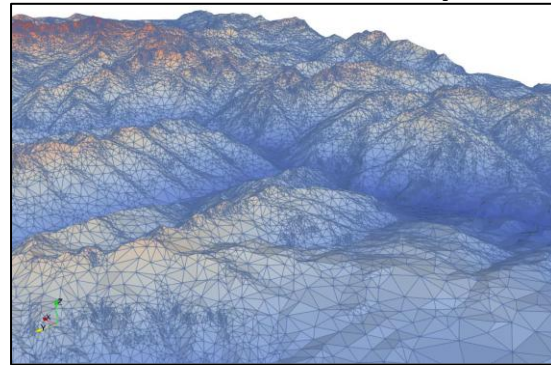
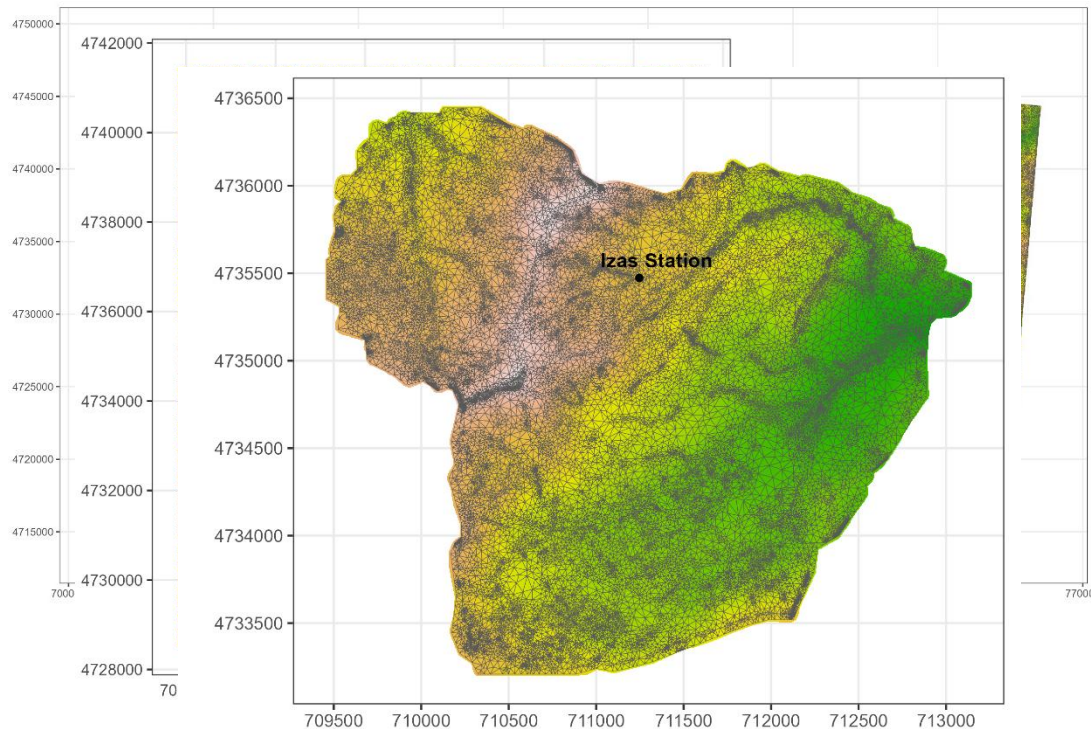
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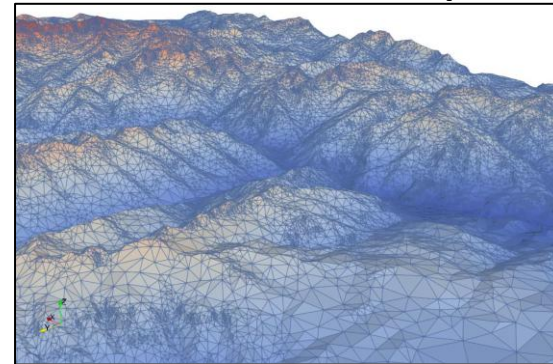
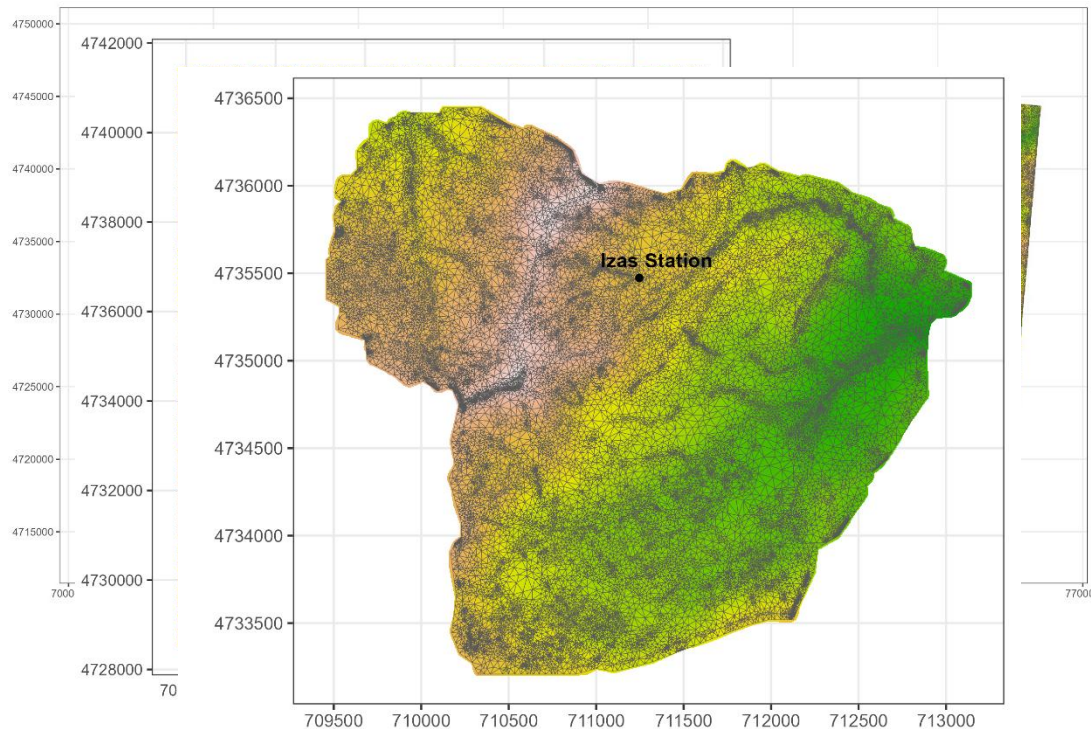
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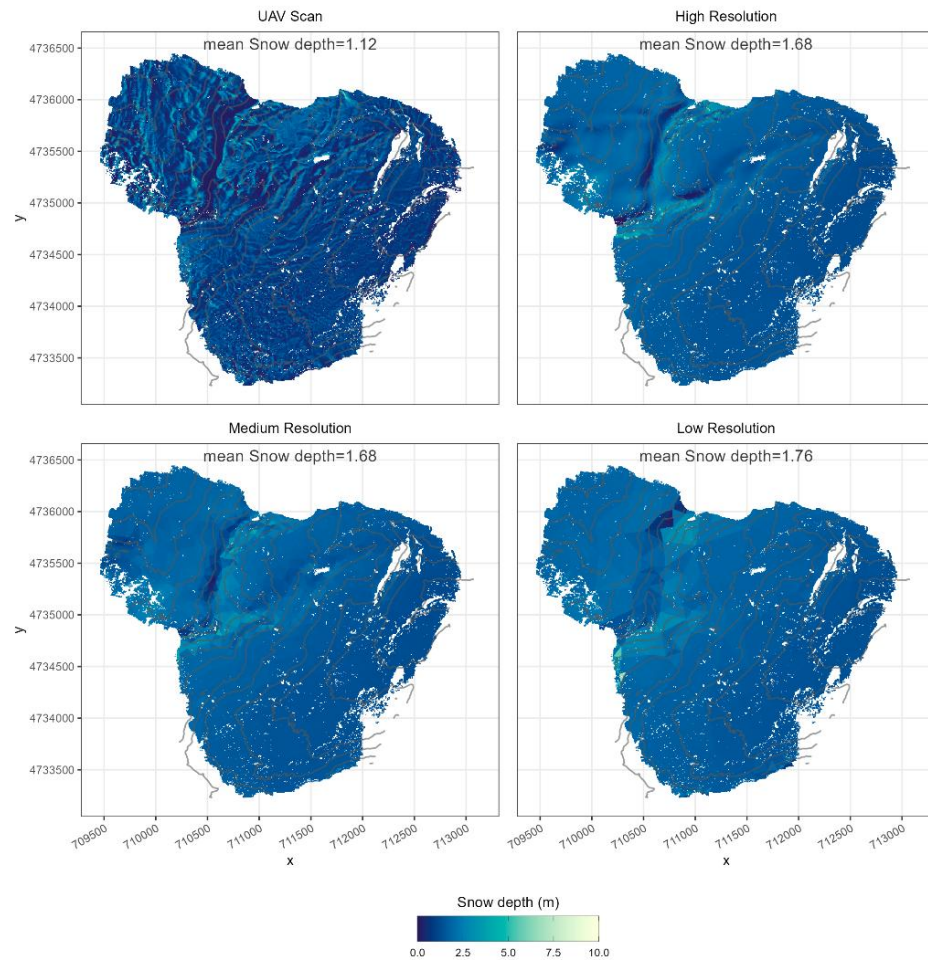
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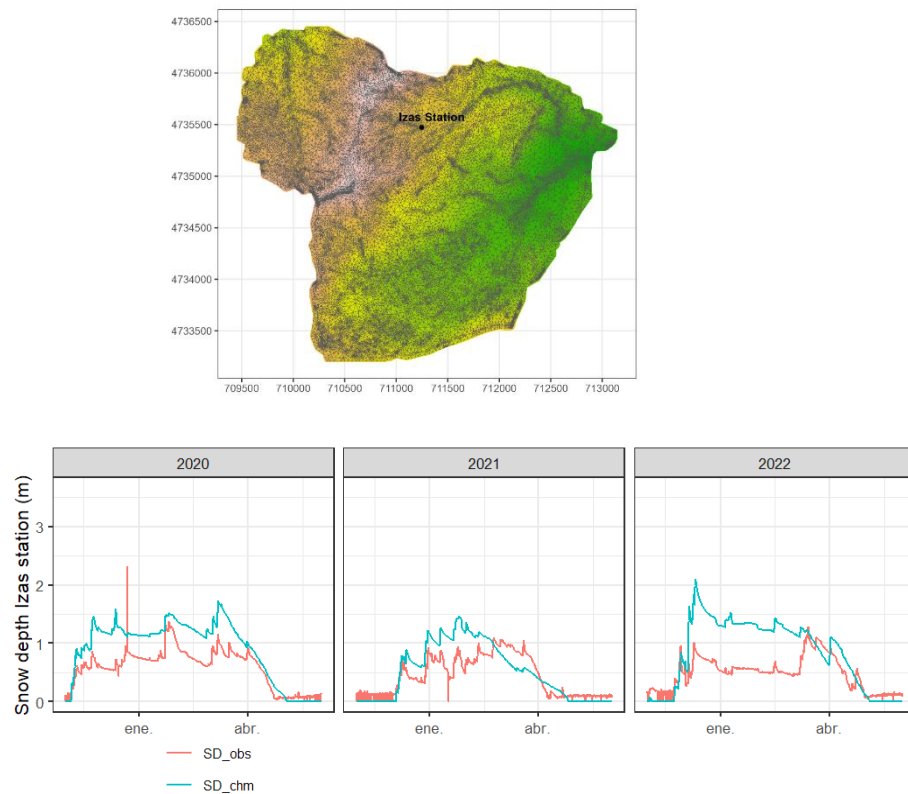


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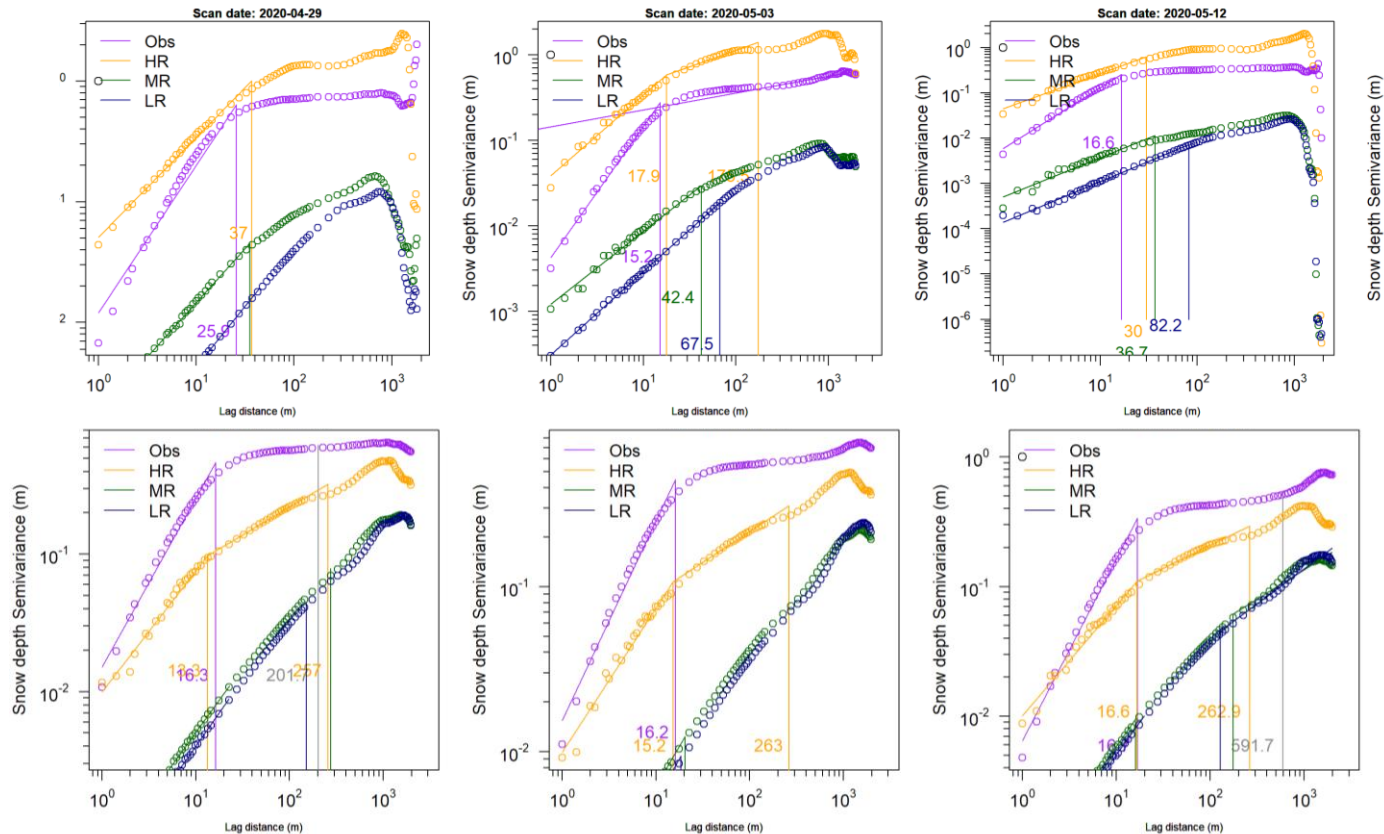
2021-12-16



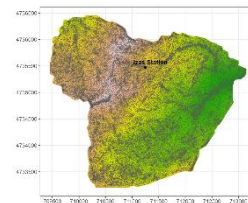
Snow Depth distribution and its temporal evolution



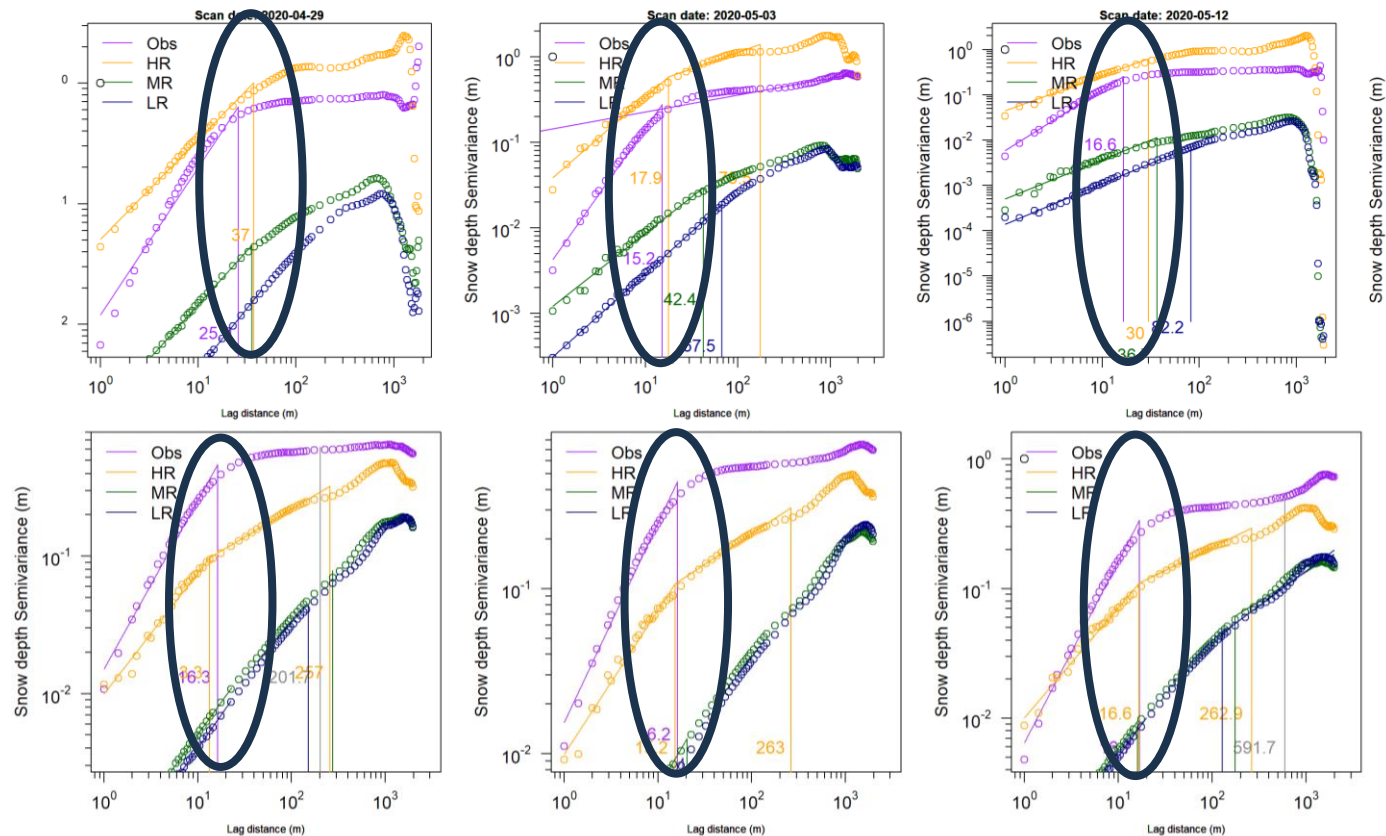
Variograms and scale breaks



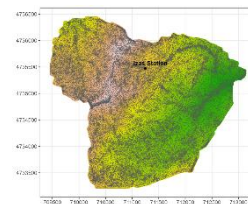
- Observed and simulated variograms in the Izas catchment for UAV scan dates, for the three different resolution models.



Variograms and scale breaks

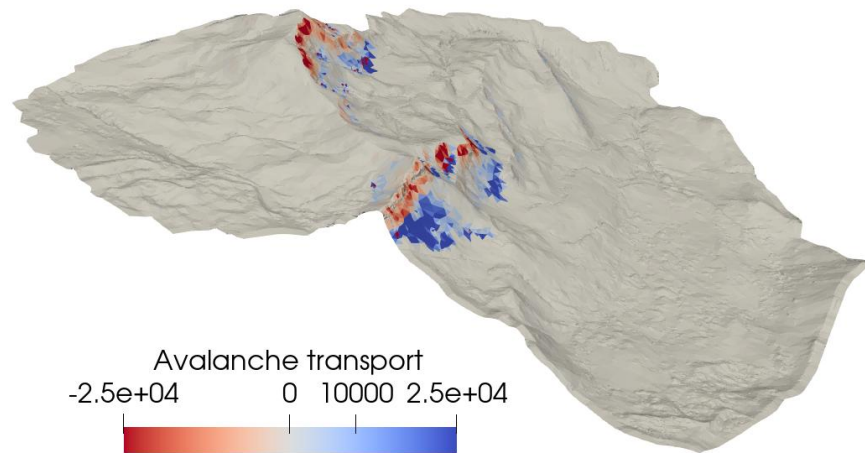
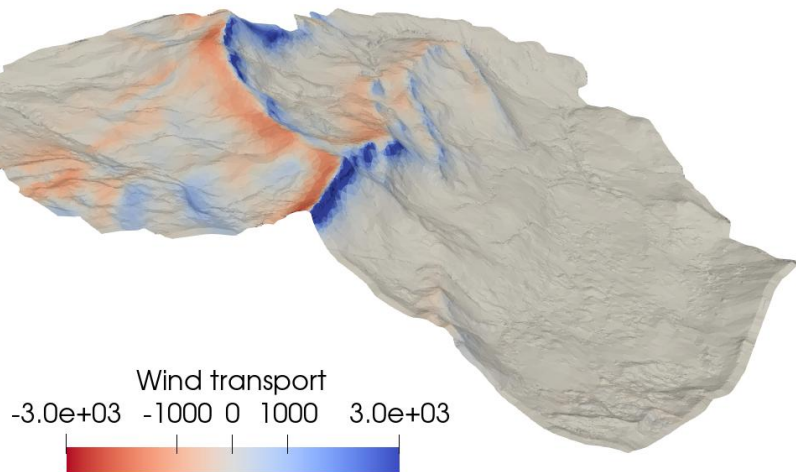


- **Observed and simulated variograms in the Izas catchment for UAV scan dates, for the three different resolution models.**
- HR model has the best representation of observed omnidirectional variograms.
- Medium and low resolution (MR and LR) models have similar results.



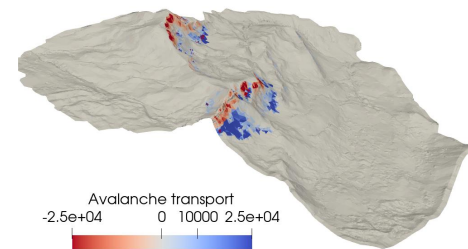
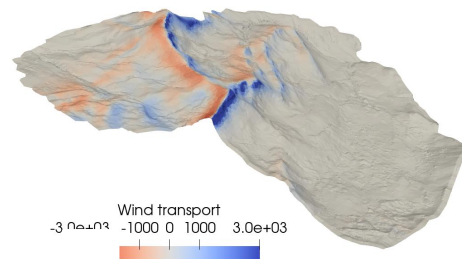
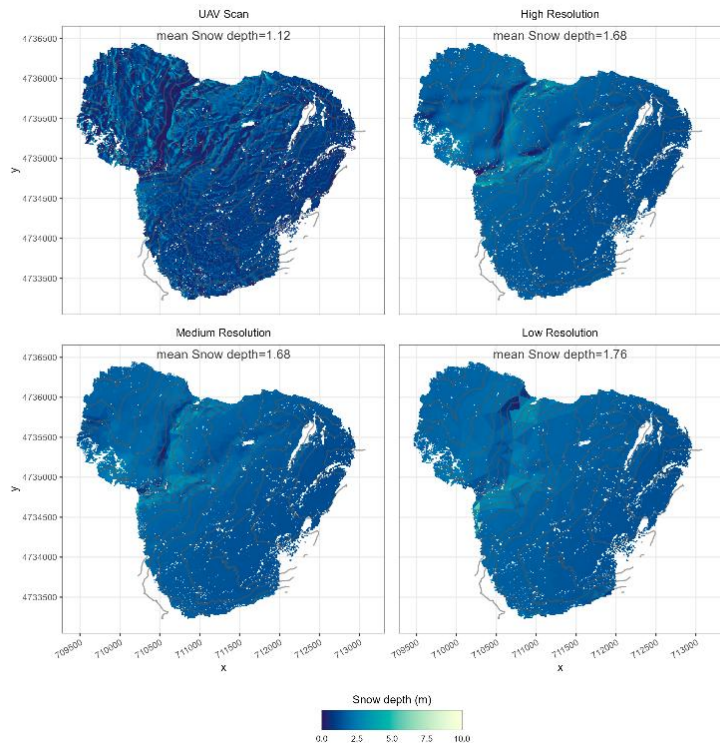
What can explain these differences in model performance?

- **Spatial distribution of snow transported by wind and by avalanches, accumulated over the 2019-2025 period for the high resolution model.**
- Snow is transported in the areas with high orographic heterogeneity: wind exposed areas show snow erosion, while wind sheltered areas show snow deposition.
- Snow deposition triggers avalanches: snow is transported to lower elevations areas.



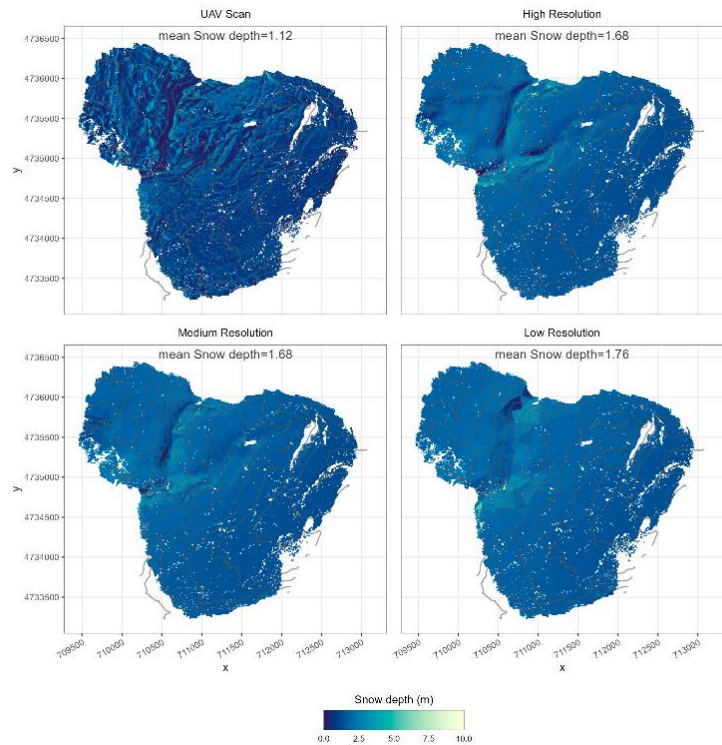
Is lateral snow transport needed to accurately reproduce snow depth distributions?

2021-12-16



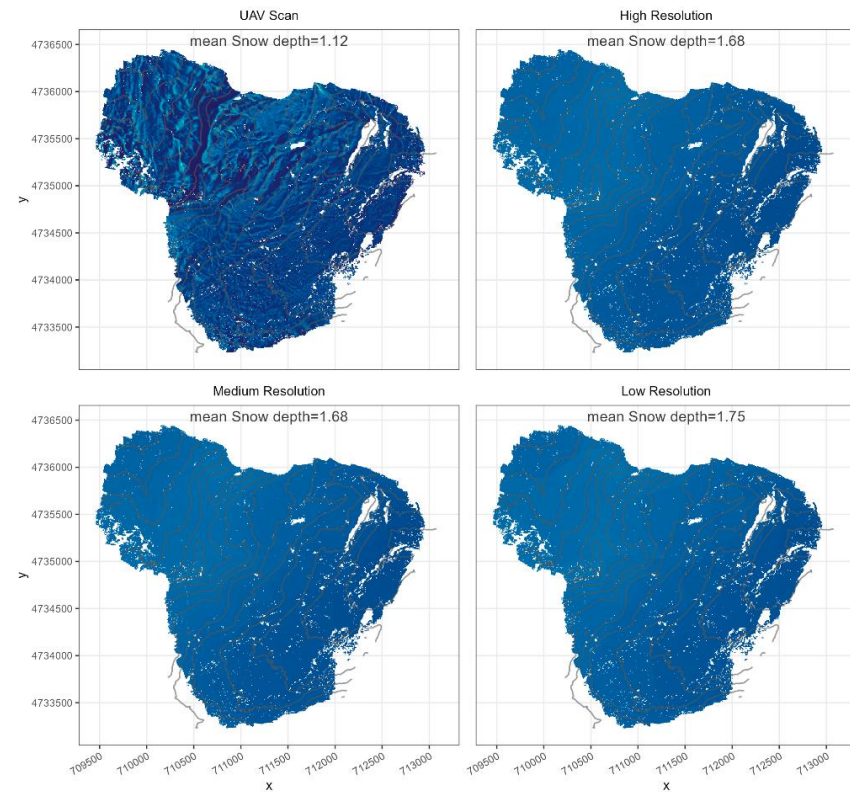
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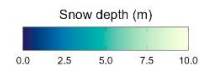


NO
TRANSPORT

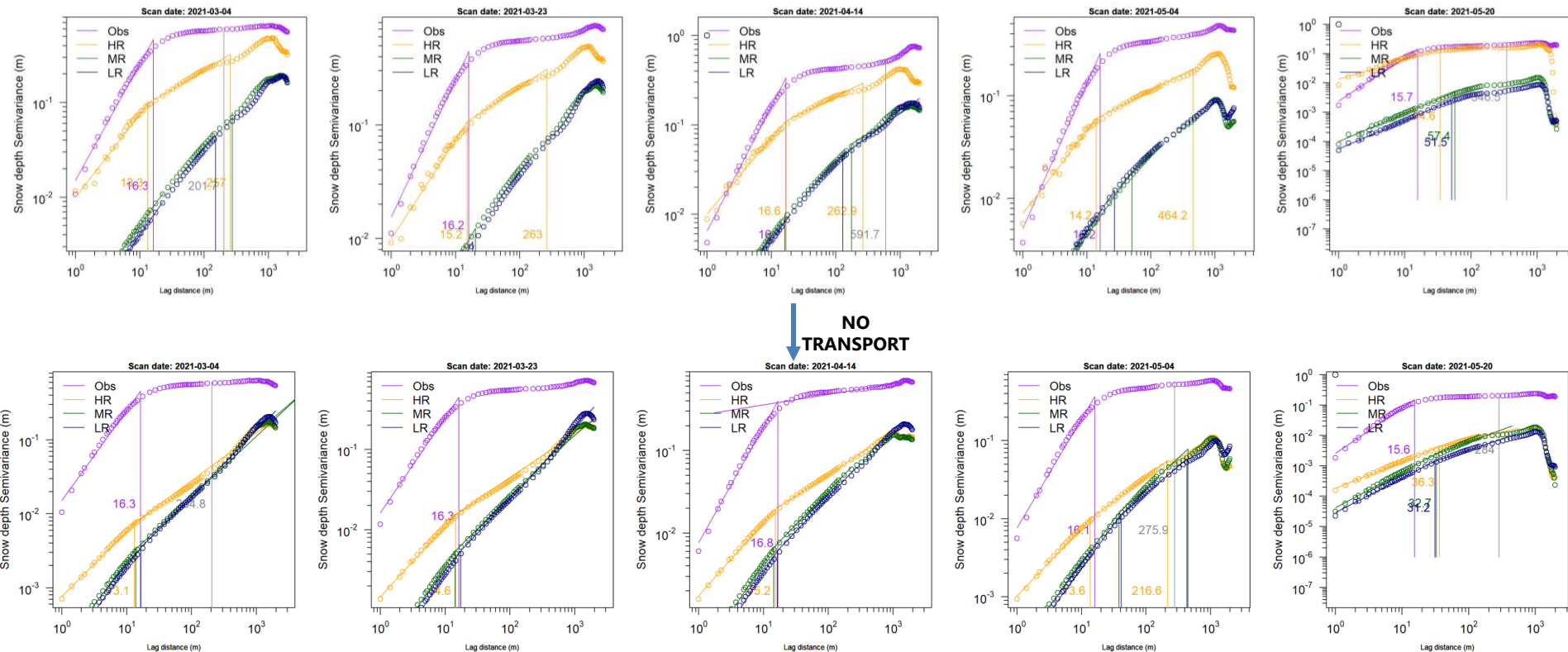
2021-12-16



- Loss of spatial patterns.



Is lateral snow transport needed to accurately reproduce snow depth distributions?



- High resolution CHM simulation reproduces variance and scale breaks with snow transport, not without.

Conclusions:

- **Temporal consistency of first scale break and fractal dimension along 10 years in small (LiDAR) and medium (UAV) domains.**
 - ✓ 25 LiDAR observations along 6 years
 - ✓ 49 UAV observations along 7 years.
- Correspondence between the **best TPI search distance the scale break and peak snow accumulation** → topography controls first scale breaks.
- **Variograms show equivalent scale breaks for distinct techniques** (not shown) and the simulations → Validation of CHM performance on simulating snow distribution.
- CHM, simulating with **high spatial resolution** and including **lateral snow transport** is able to **reproduce the snow scaling behaviour**.

Scale Breaks in Snow Depth Distribution and Their Topographic Controls: Insights from Remote Sensing and CHM

J. Revuelto¹, M. Courard¹, P. Mendoza², C. Marsh³, I. Goutevin⁴,
F. Rojas-Heredia¹, J.I. López-Moreno¹

¹ Instituto Pirenaico de Ecología, CSIC, Zaragoza, Spain

² Ingeniería civil, Universidad de Chile, Santiago de Chile, Chile

³ Environment and Climate Change, Canada

⁴ Centre d'Etudes de la Neige CNRM, Grenoble, France

⁵ Géographie de l'environnement, CNRS, Toulouse, France



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Thanks!

