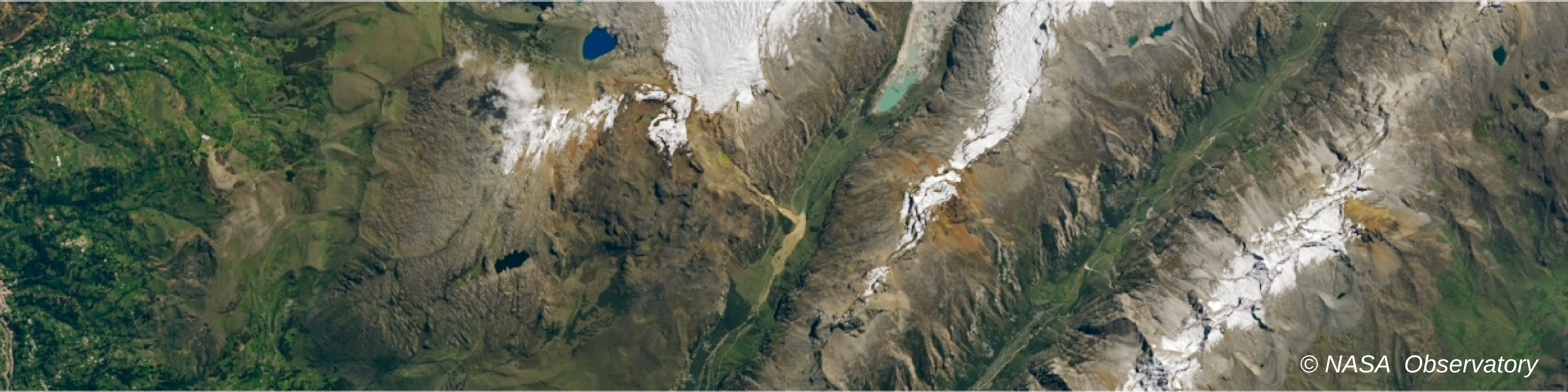
April 28, 2025 Vallunaraju GLOF
Insights from high resolution satellite imagery



Dr. Diego CUSICANQUI[1,*] and many others

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6 Nov, 2025

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What are we talking about?

1 – Glacial Lakes Outburst Floods (GLOFs)

→ Where is it found?

→ How they work?

→ GLOFs in Peru

2 – Vallunaraju GLOF, small . . . but destructive event?

→ Characterization of the event from Pléiades

→ Role of sediment availability

3 – Beyond the hazard . . .

→ Increasing vulnerability?

4 – Conclusions

Context | GLOF

↗ climate change

↘ glaciers

↗ glacier lakes

↗ hazards

Socio-economic and environmental impact

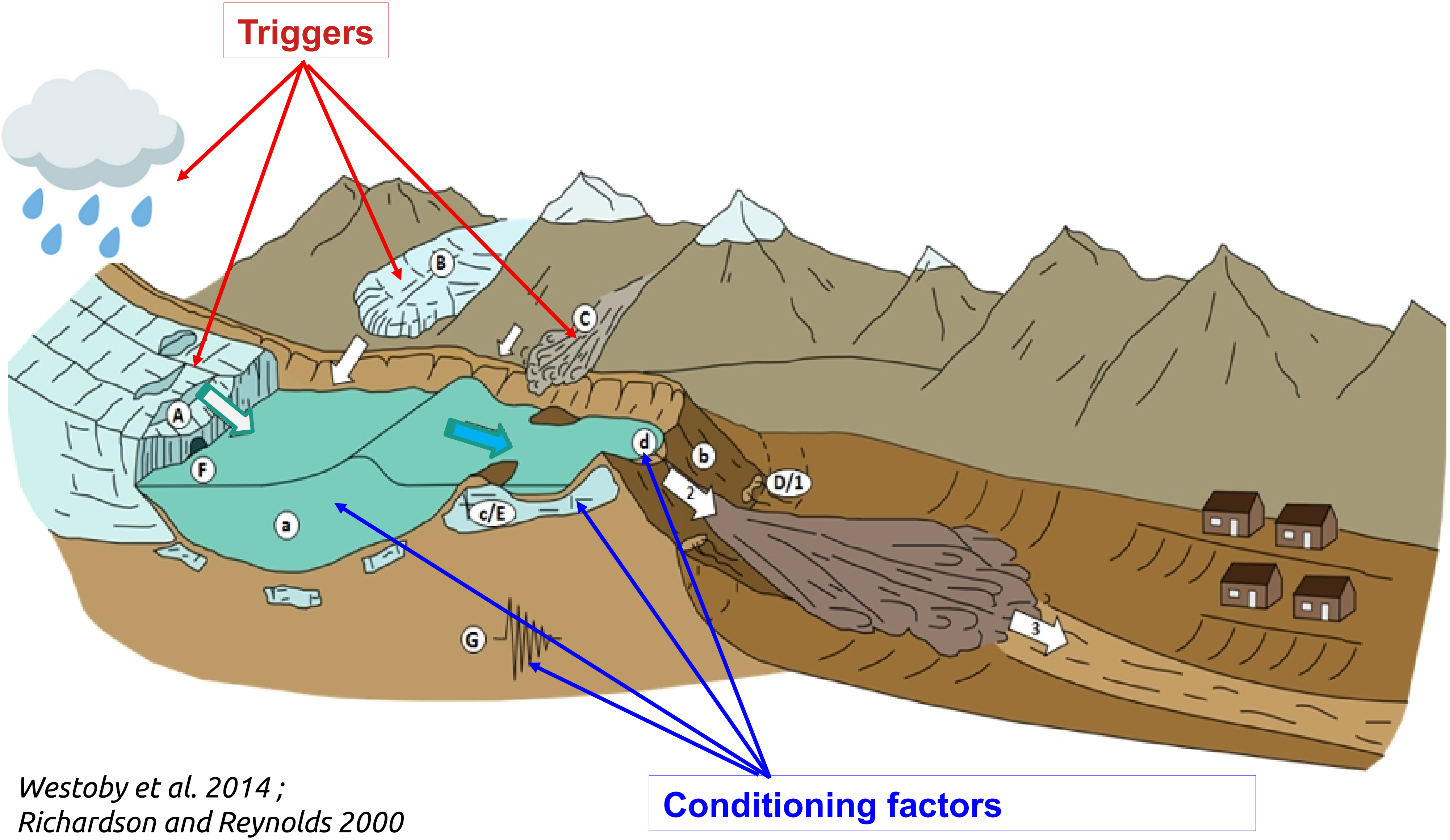
hydro-electric dams

Glacier reservoirs

supra-glacial lakes

pro-glacial lakes

Context | Elements of GLOF



Westoby et al. 2014 ;
Richardson and Reynolds 2000

Context | Elements of GLOF

RISK = HAZARD x VULNERABILITY

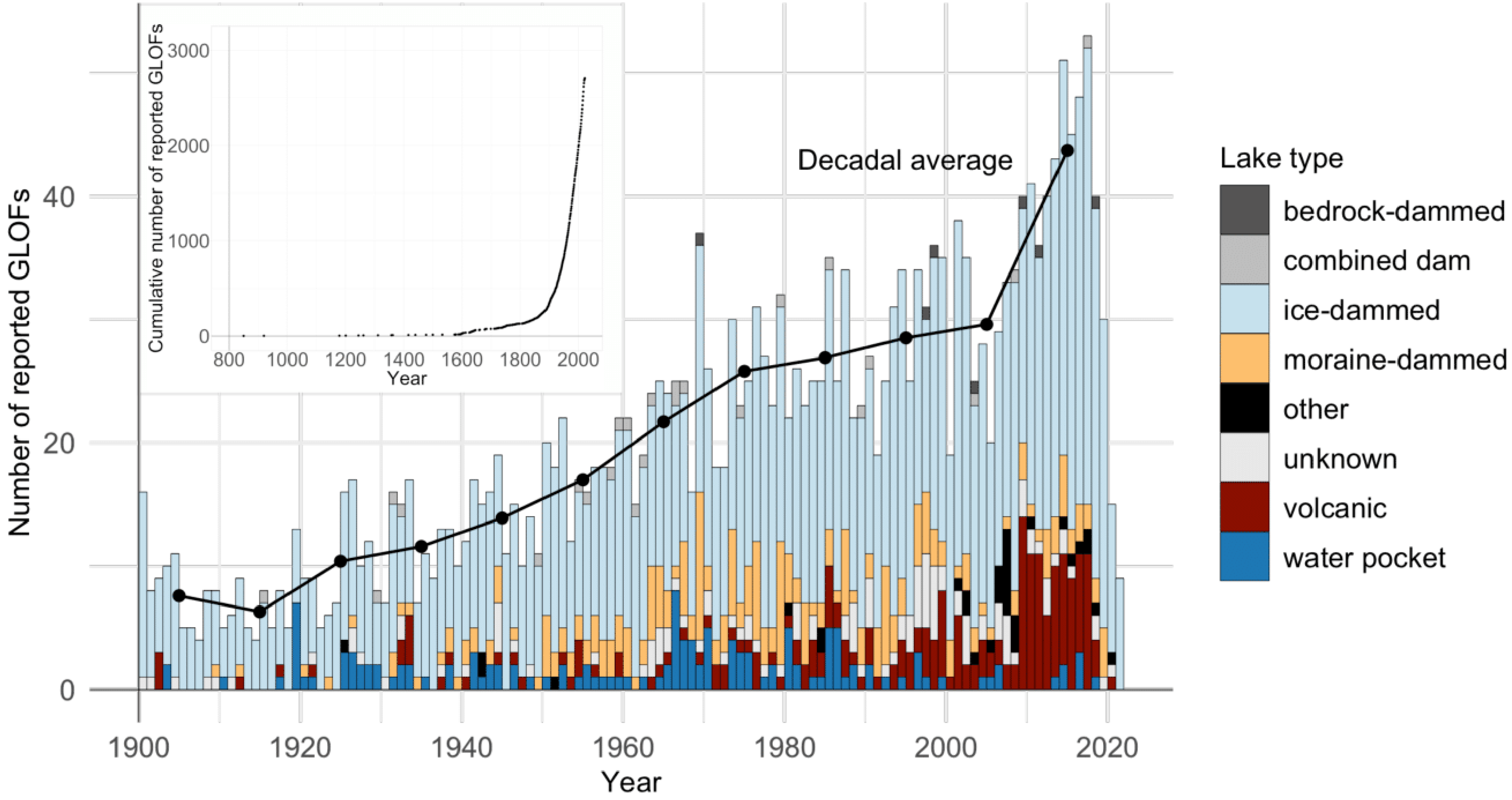
18 million m³ !!!
30,000 m³/s

… 200 km!

Allen et al., 2015

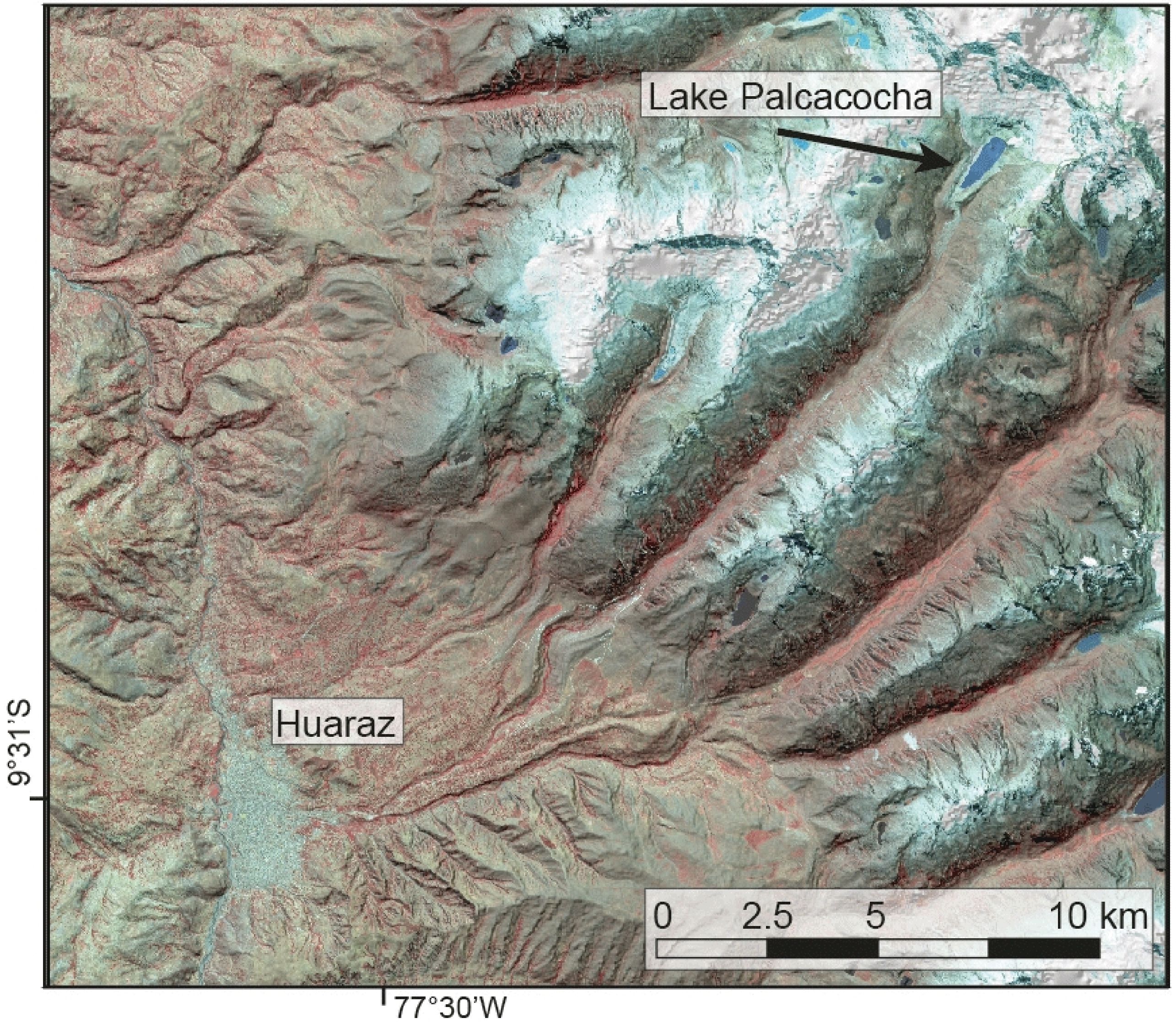
Westoby et al. 2014 ;
Richardson and Reynolds 2000

Context | Elements of GLOF



Lützow et al., 2023

Context | GLOF in Peru



Huggel et al., (2022). GLOF, risks, global drivers and responsibilities

Huaraz city (post-GLOF)

Huaraz city (2020)

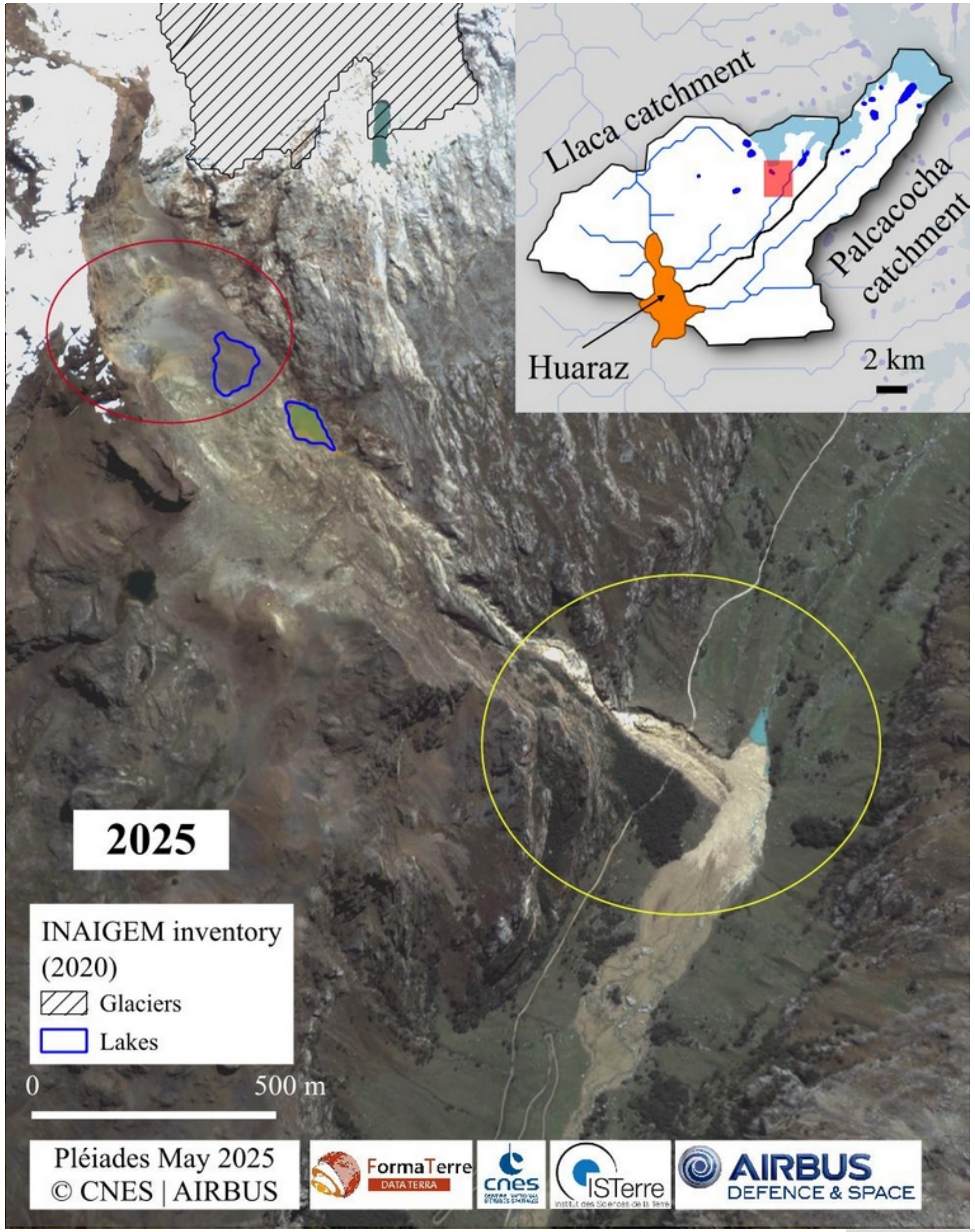
- GLOF triggered by landslide.
- Destroyed 1/3 of the city and killed 5,000 people

Vallunaraju GLOF | Context of the event

- On 28 April, 2025, a rockslide has suddenly fall into two periglacial lakes (called hereafter Lake A and B) at left flank of Vallunaraju glacier (~5 000 m a.s.l.).

- Rockfall has completely empty both lakes generating a debris flow downstream.

- The debris-flow reached the lower part of the Casca sub-basin causing damage and losses to homes in the district of Independencia.

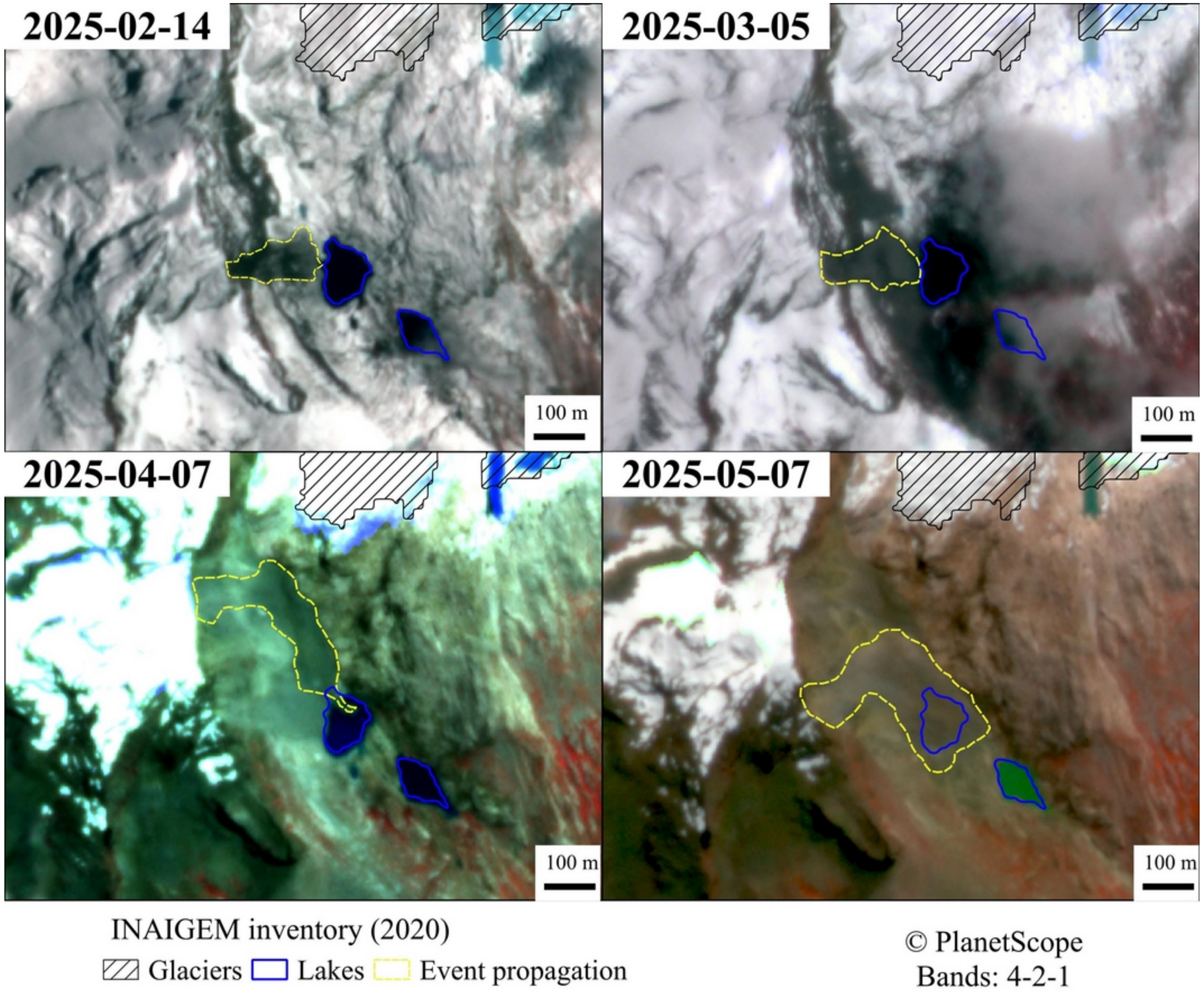


Cusicanqui & Lacroix (2025). CIEST² communication

Results | PlanetScope imagery

- **2025-02-14:** Small detachment. This event do not reach the lake.
- **2025-03-05:** Second detachment. Same source but bigger.
- **2025-03-26:** Third detachment. 100 meters above the first event. Rockfall reach the lake and provoked an <u>small overflow of both lakes</u>. The route to Llaca glacier has been alredy impacted.
- **2025-04-28:** Main and bigger event. Close to the same source of the two first events. This event has completely empty both lakes causing a cascade event.

- 4 precursory events **three months before to the main avent!!**



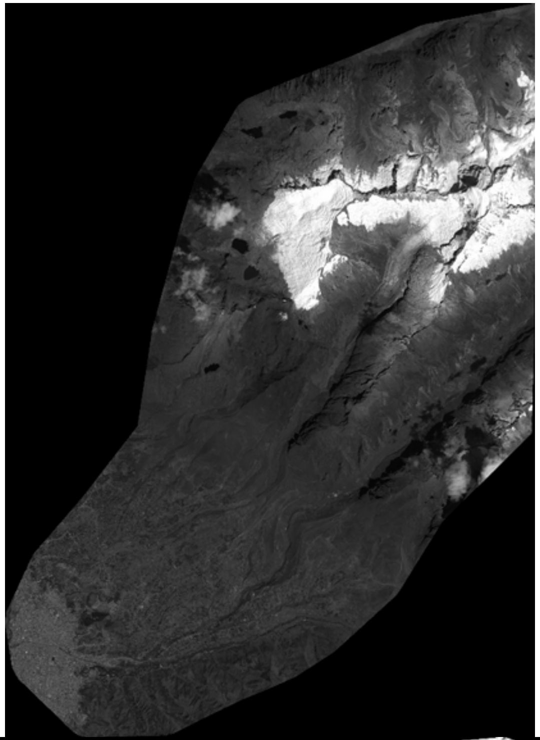
Results | Pléiades DEMs

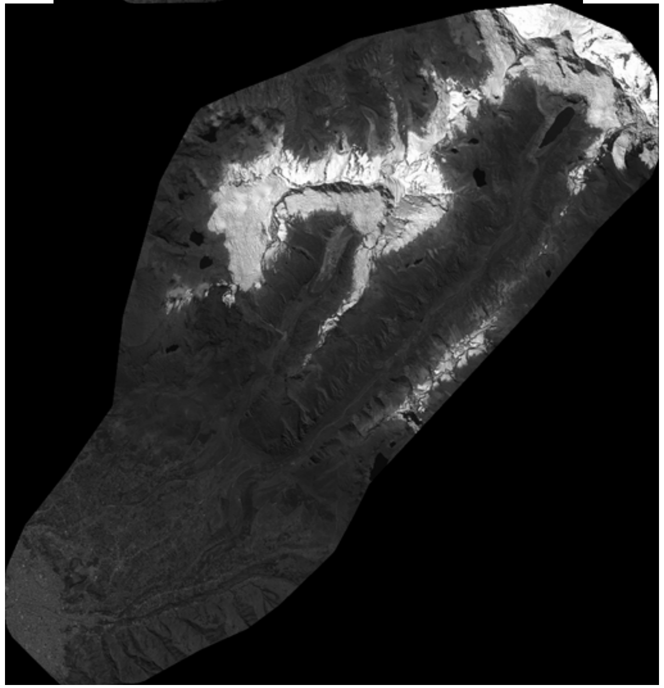
- Two Pléiades stereo acquisition (9 year of interval) were served to evaluate impacts for the event and volumetric changes.

- **Pléiades 02-01-2016:**
  - Slightly saturated due to fresh snow patches.
  - Large spatial coverage.

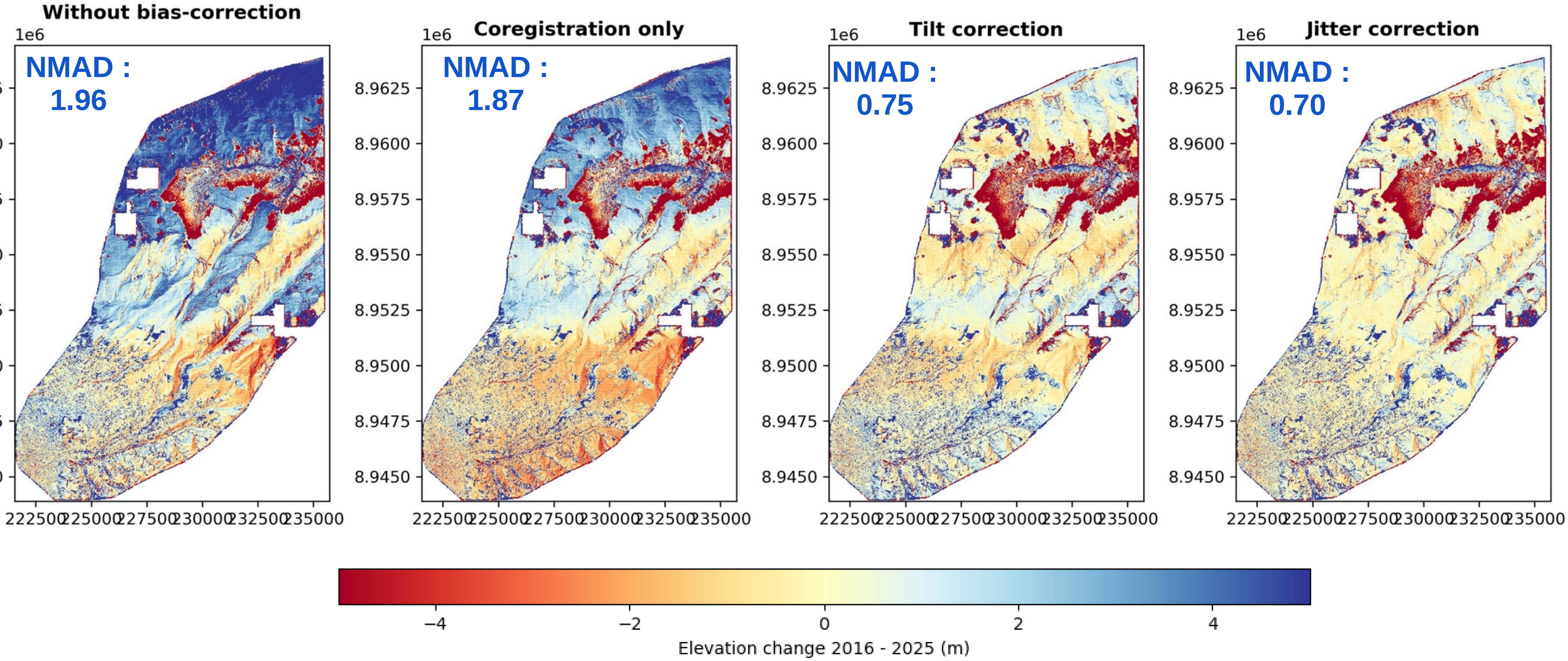
- **Pléiades 07-05-2025:**
  - Restricted spatial coverage
  - Source: Dinamis & CIEST²

- Both DEMs were processes automatically with ASP using robust approach (*Cusicanqui et al., 2023, Berthier et al., 2025*)

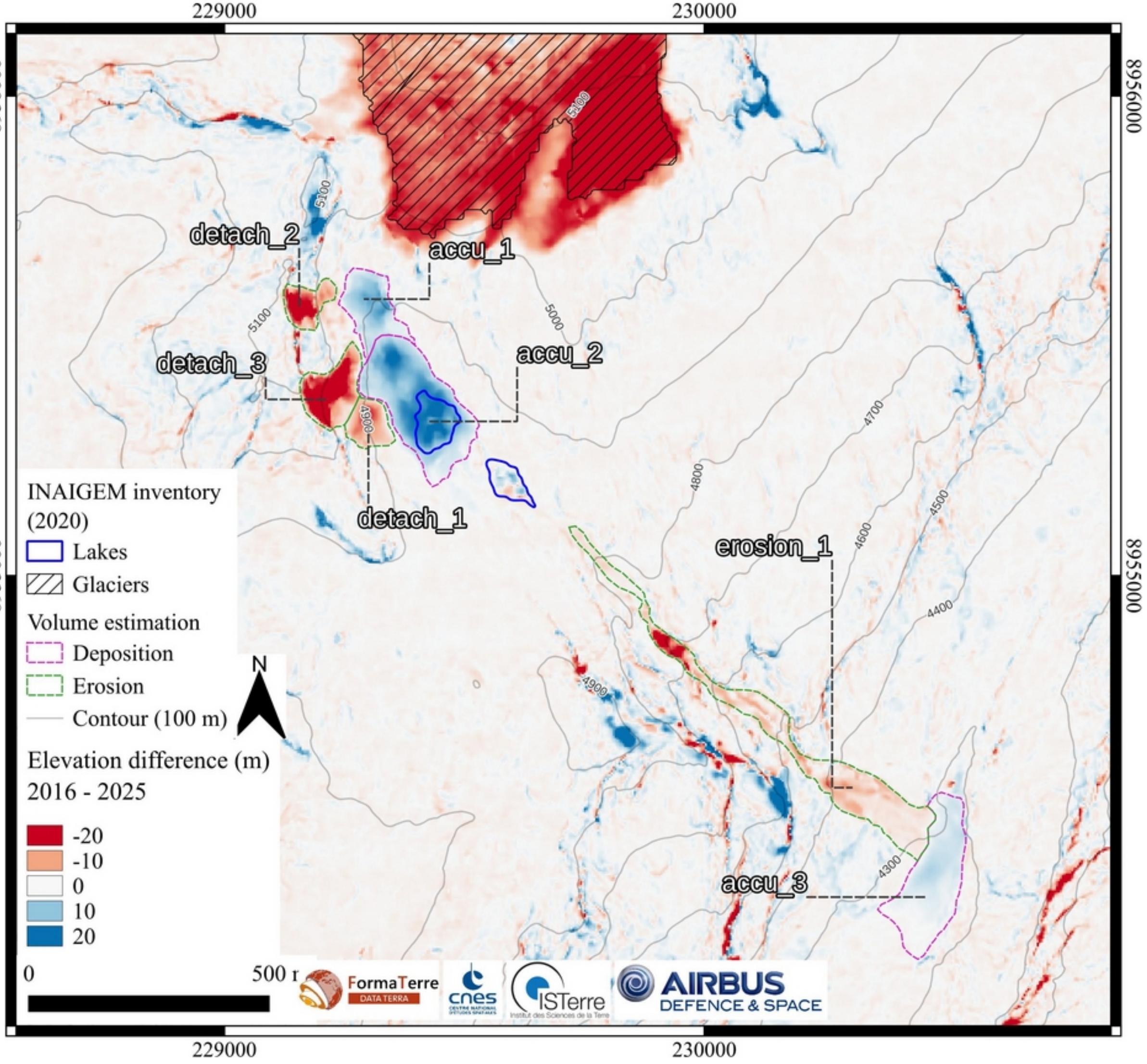




Results | DEM corrections



Results | Rockfall volume estimation

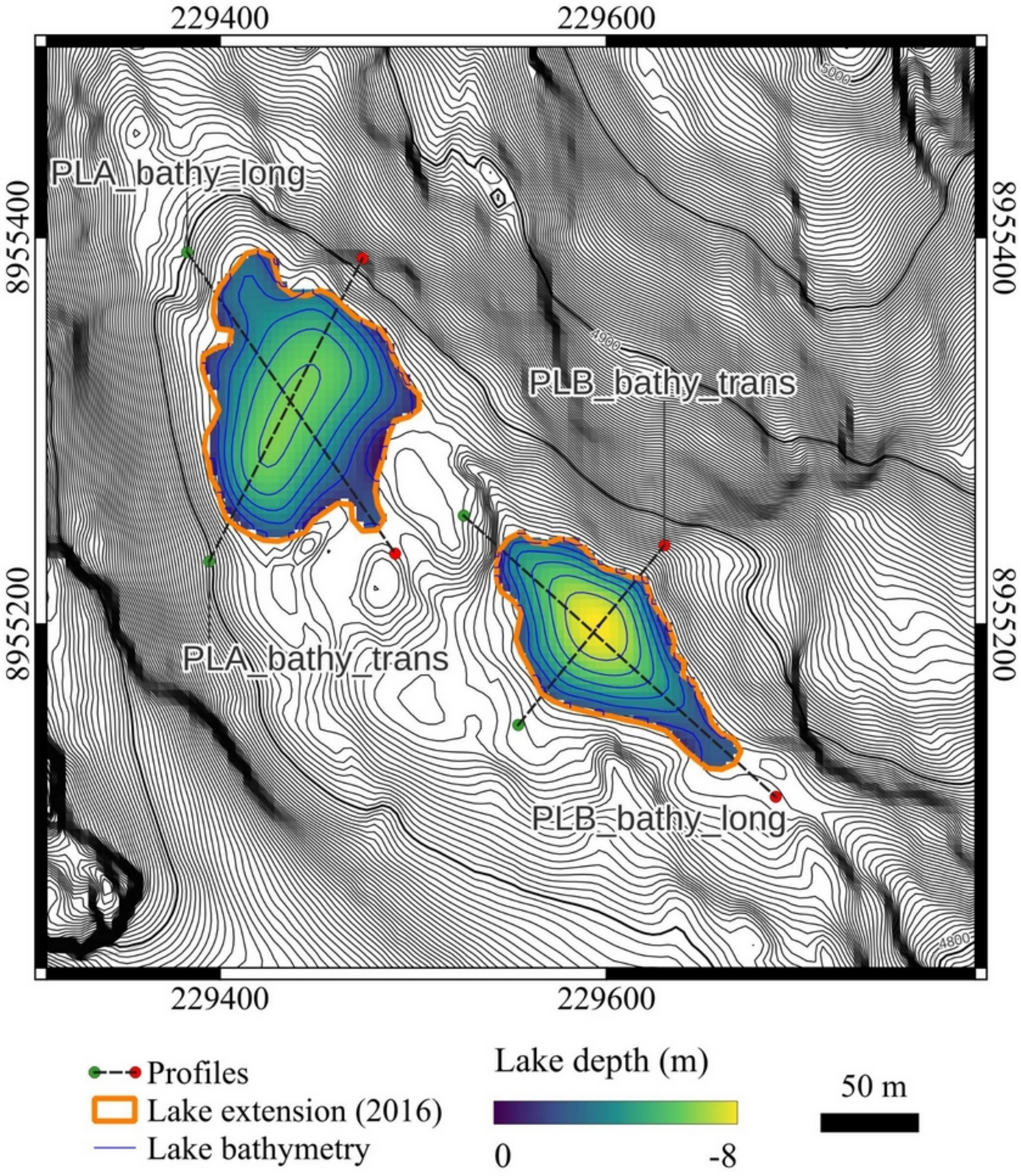


type	avg dh m	max dh m	Vol m³	vol_err m³
detach_1	-7,7	-17,2	-60 139,7	1 997,4
detach_2	-13,8	-40,5	-101 472,4	1 943,3
detach_3	-19,0	-60,8	**-269 233,3**	2 692,6
accu_1	6,2	16,5	88 915,1	2 700,2
accu_2	10,7	29,1	423 825,6	4 511,9
	TOTAL	**detach**	**-430 845,4**	6 633,3
		accu	512 740,8	7 212,0
		diff	81 895,41	-

$$Volume = \sum_{i=1}^{n} (\Delta h_i \dot{A}) \qquad \sigma_{\Delta h} = \sqrt{\sigma_{DEM_1}^2 + \sigma_{DEM_2}^2} \qquad \sigma_V = \sigma_{\Delta h} \cdot A \cdot \sqrt{n}$$

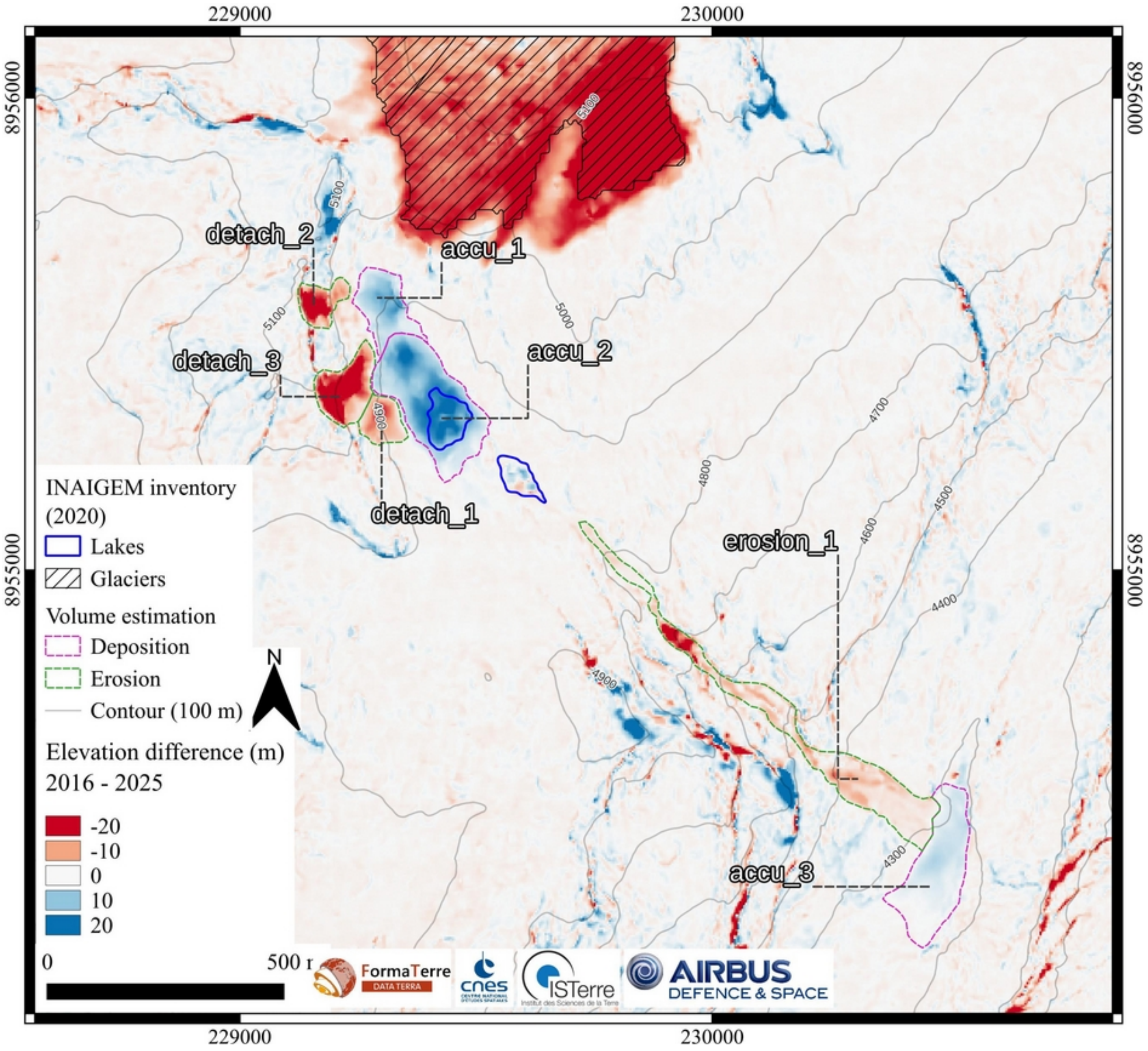
Δh = Elevation changes ; A = Surface (m²) ; n = pixels

Results | Lakes volume estimation



lake	Surface m²	Avg depth h m	Max depth hm	Vol m³	vol_err m³
A	11 199,42	-3,84	-6,43	42 747,61	2 986,90
B	7 245,49	-4,45	-8,03	32 483,90	2 421,24
		TOTAL		**75 231,51**	**5 408,14**

Results | Erosion volume estimation

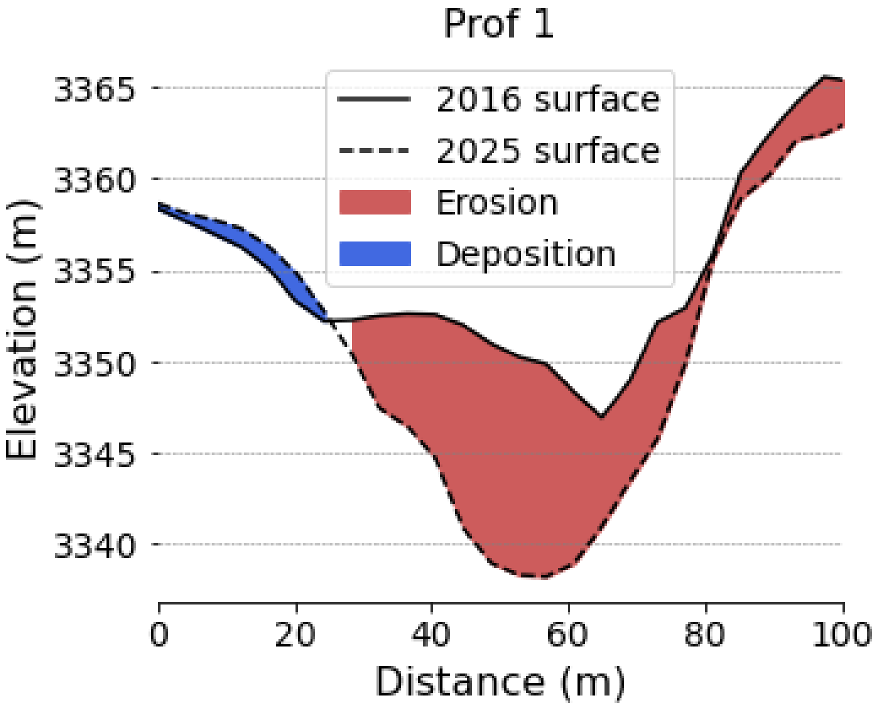


type	avg_dh m	max_dh m	Volume m³	vol_err m³
erosion_1	-4,28	-44,33	-185 997,51	4 715,20
accu_3	2,05	7,08	63 874,98	3 989,62
		Diff	**-122 122,52**	

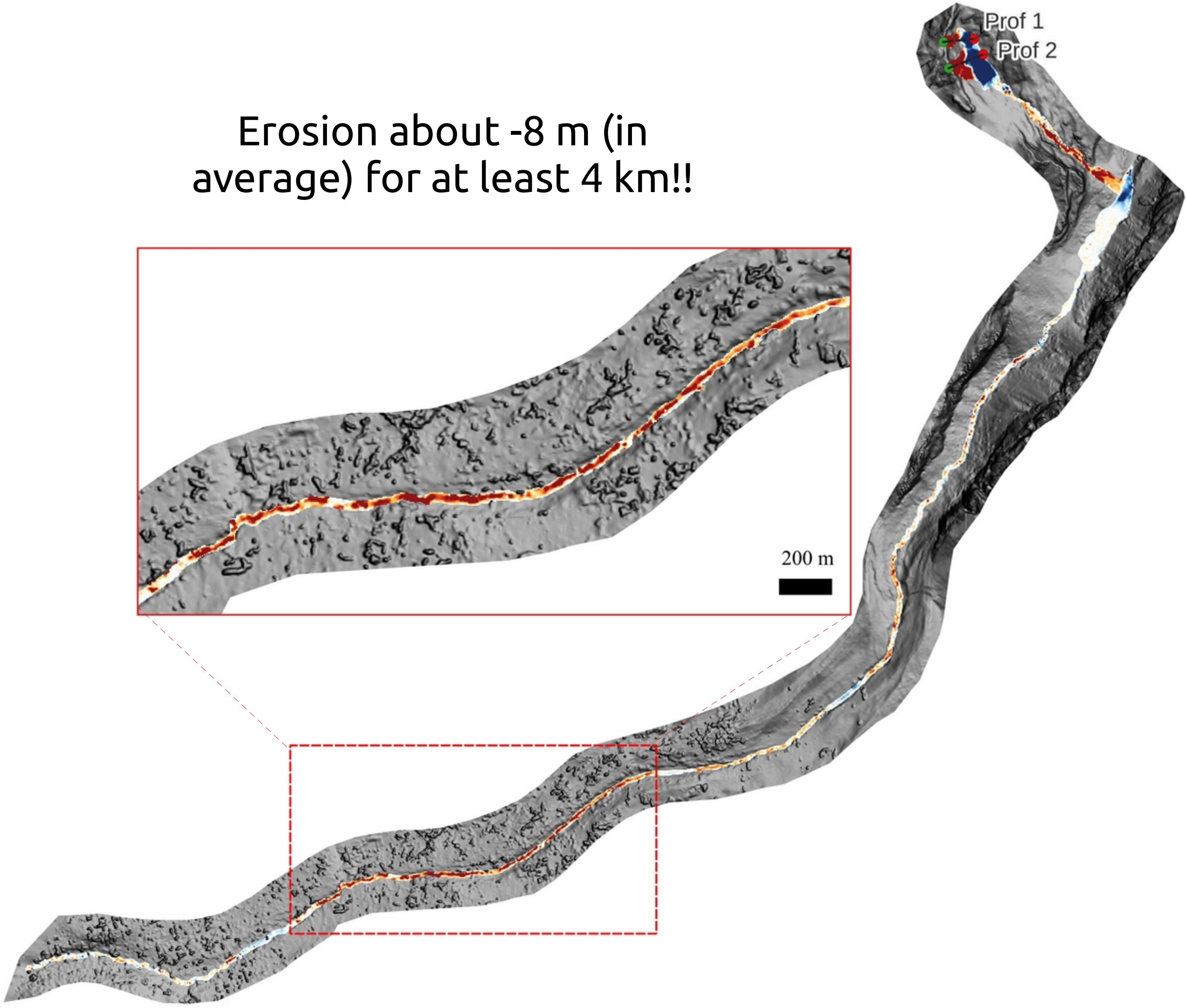
$$Volume = \sum_{i=1}^{n} (\Delta h_i \dot{A}) \qquad \sigma_{\Delta h} = \sqrt{\sigma^2_{DEM_1} + \sigma^2_{DEM_2}} \qquad \sigma_V = \sigma_{\Delta h} \cdot A \cdot \sqrt{n}$$

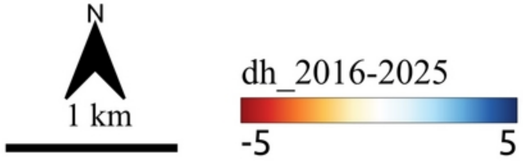
Δh = Elevation changes ; A = Surface (m²) ; n = pixels

Results | Sediment Transport Analysis

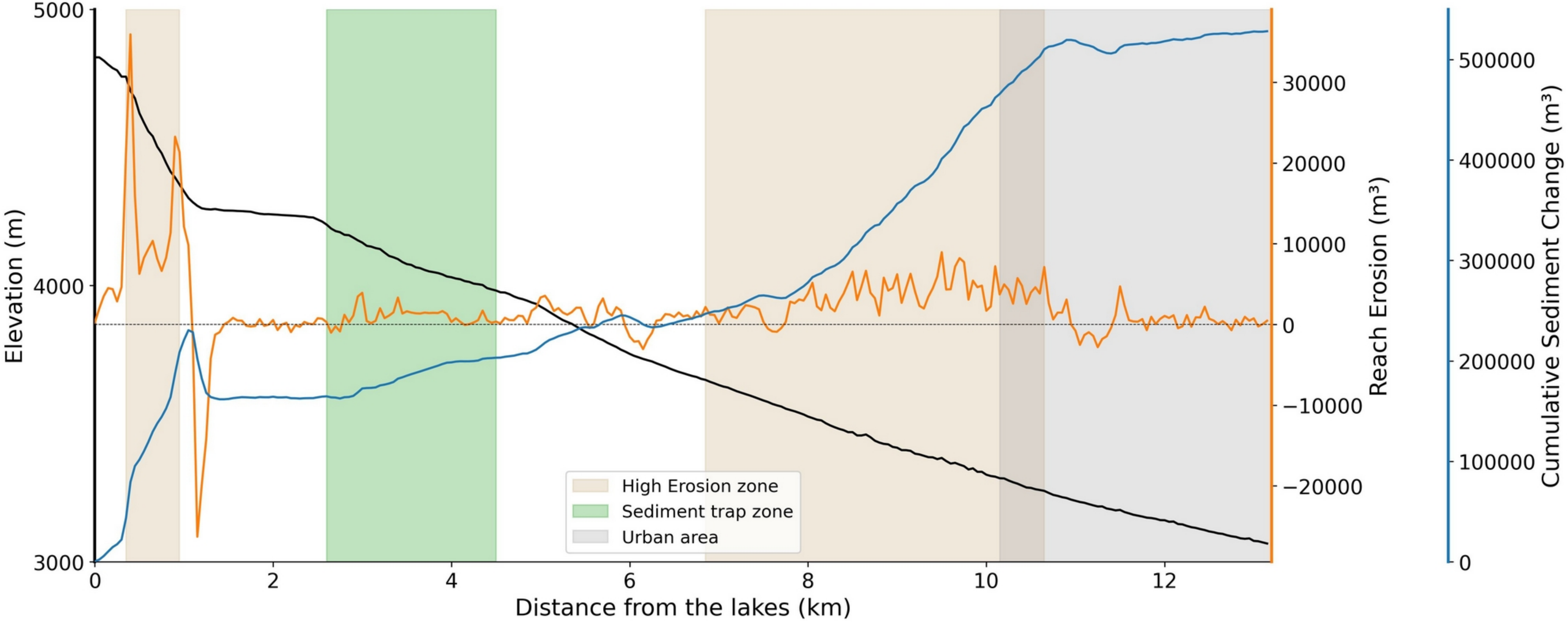


Erosion about -8 m (in average) for at least 4 km!!



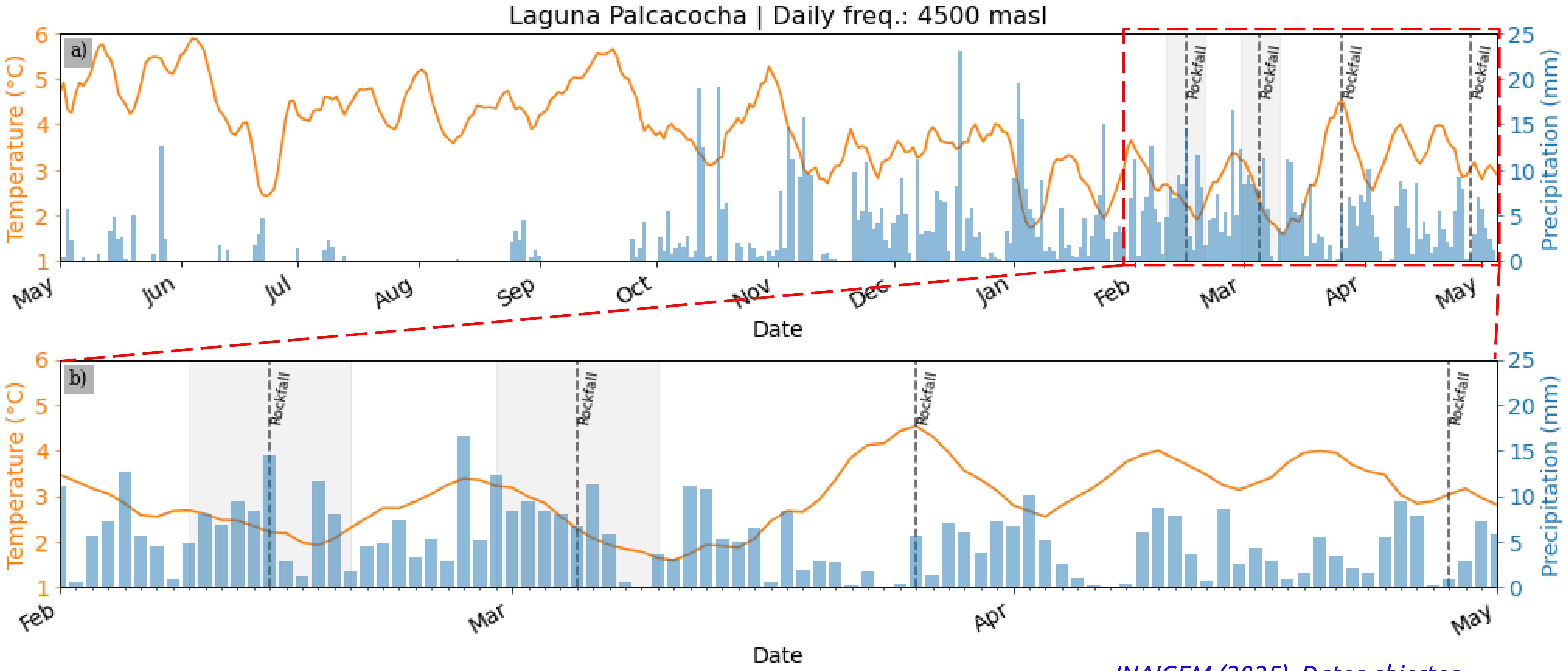


Results | Sediment Transport Analysis



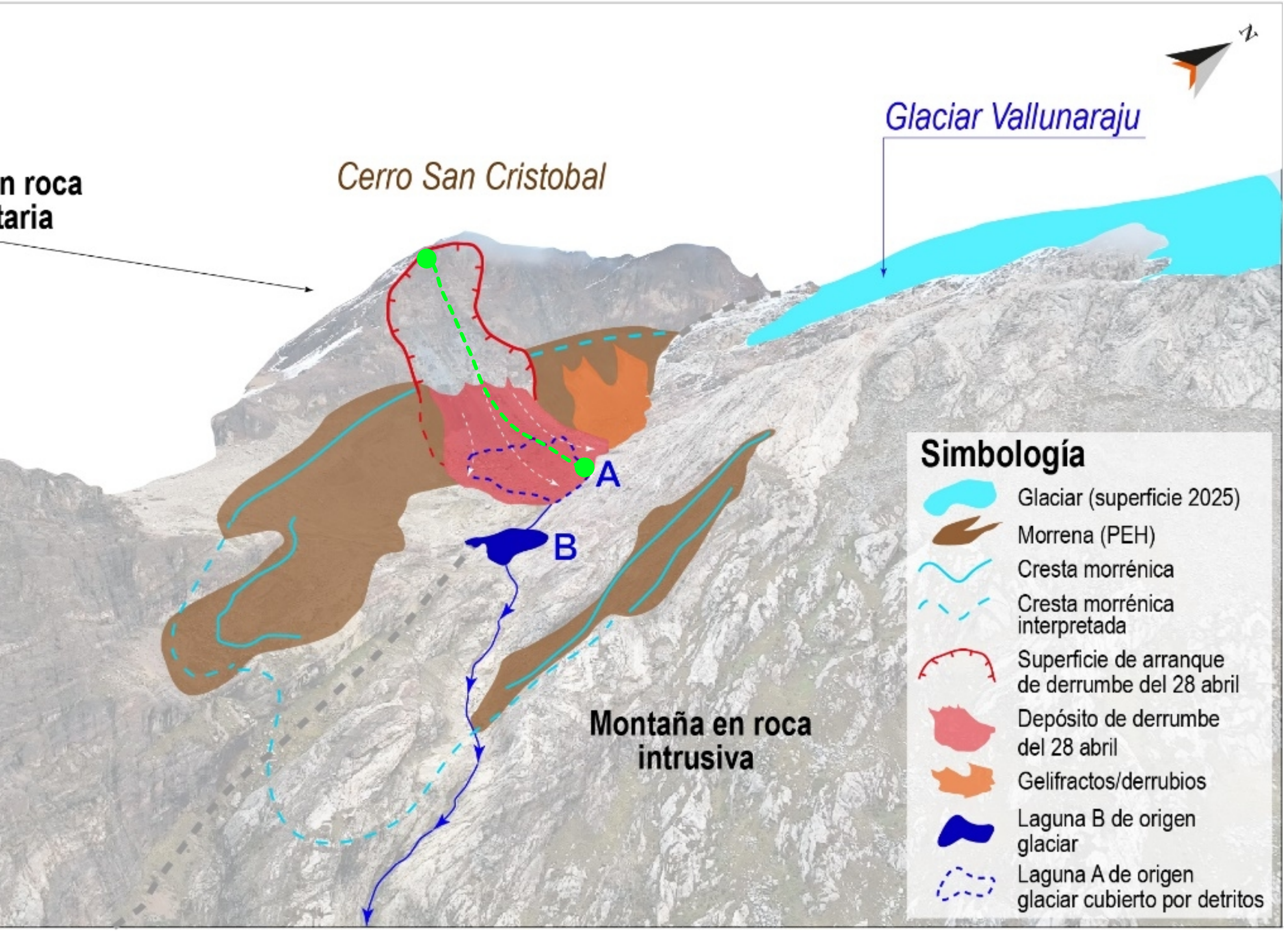
The total accumulated volume that reached the city was **7 times** the initial volume.

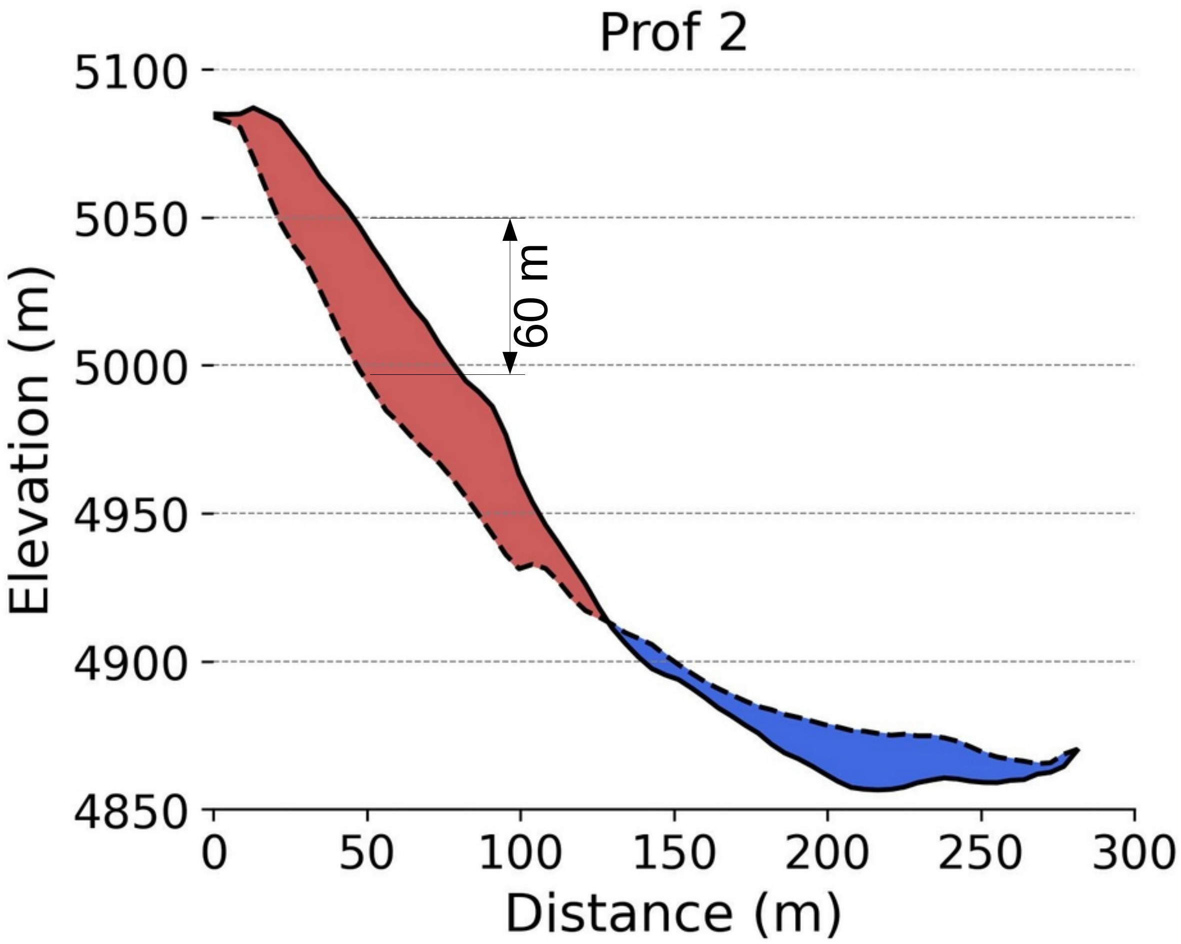
Discussion | Short term weather (local weather station)



INAIGEM (2025). Datos abiertos

Discussion | Inherited permafrost conditions

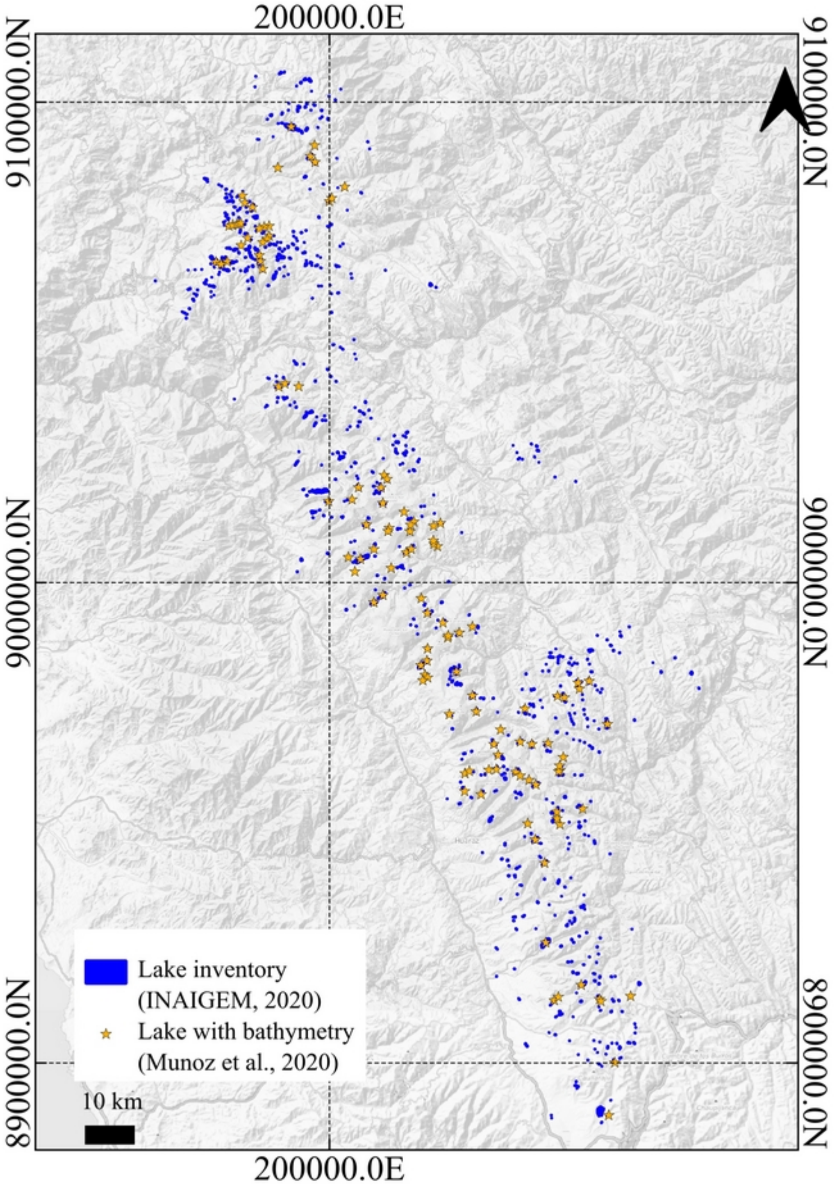


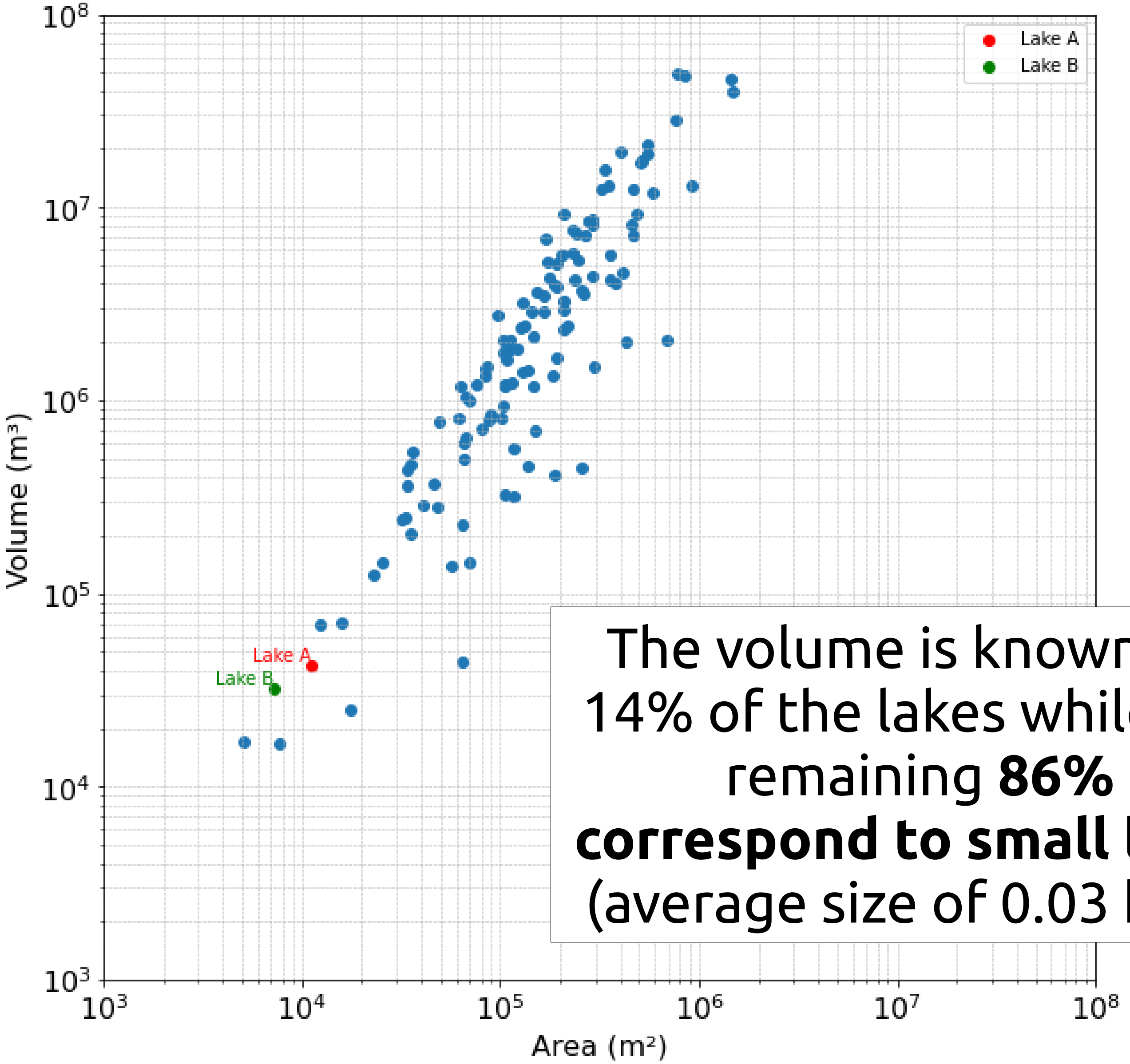


INAIGEM & INGEMET (2025). Vallunaraju GLOF report

Modeling of temperature propagation is required . . . **Ongoing work**

Discussion | Volumetric context of the Vallunaraju GLOF

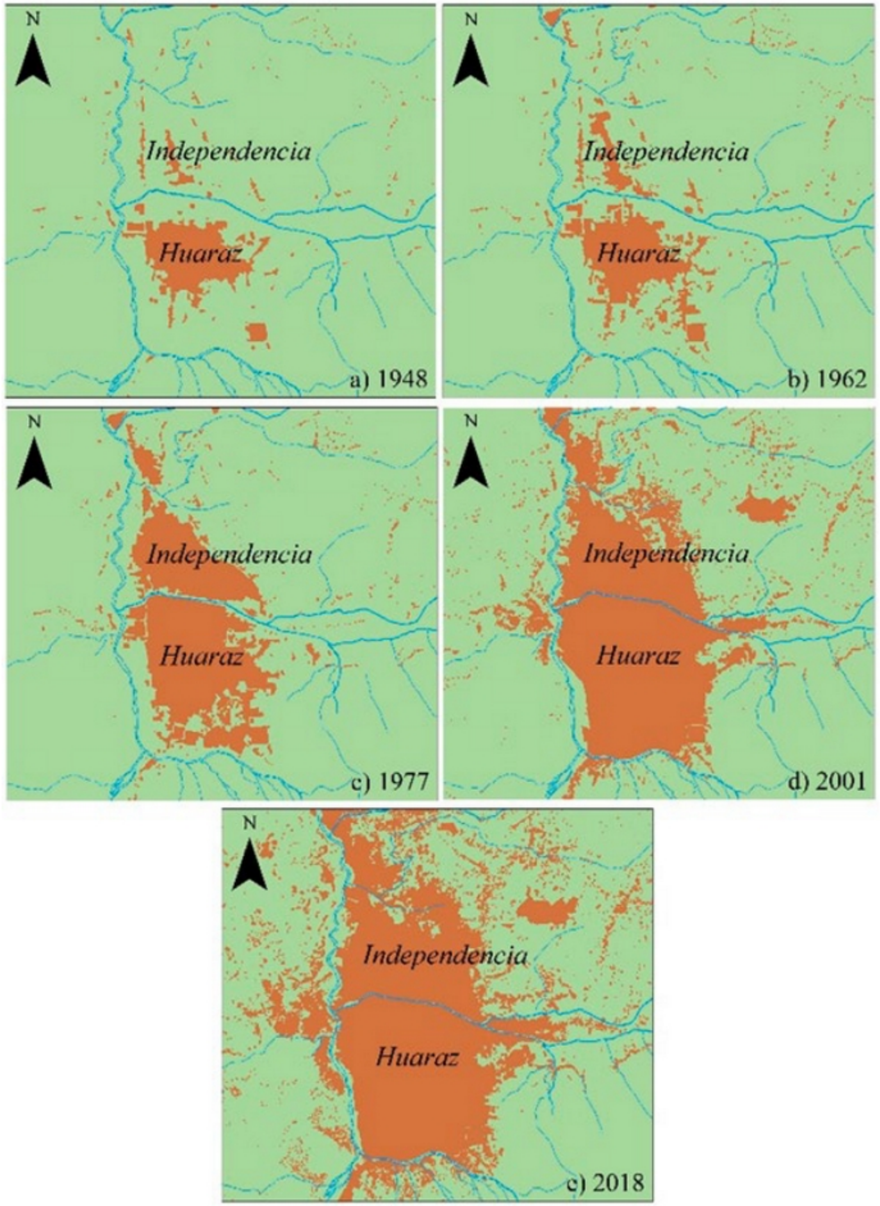


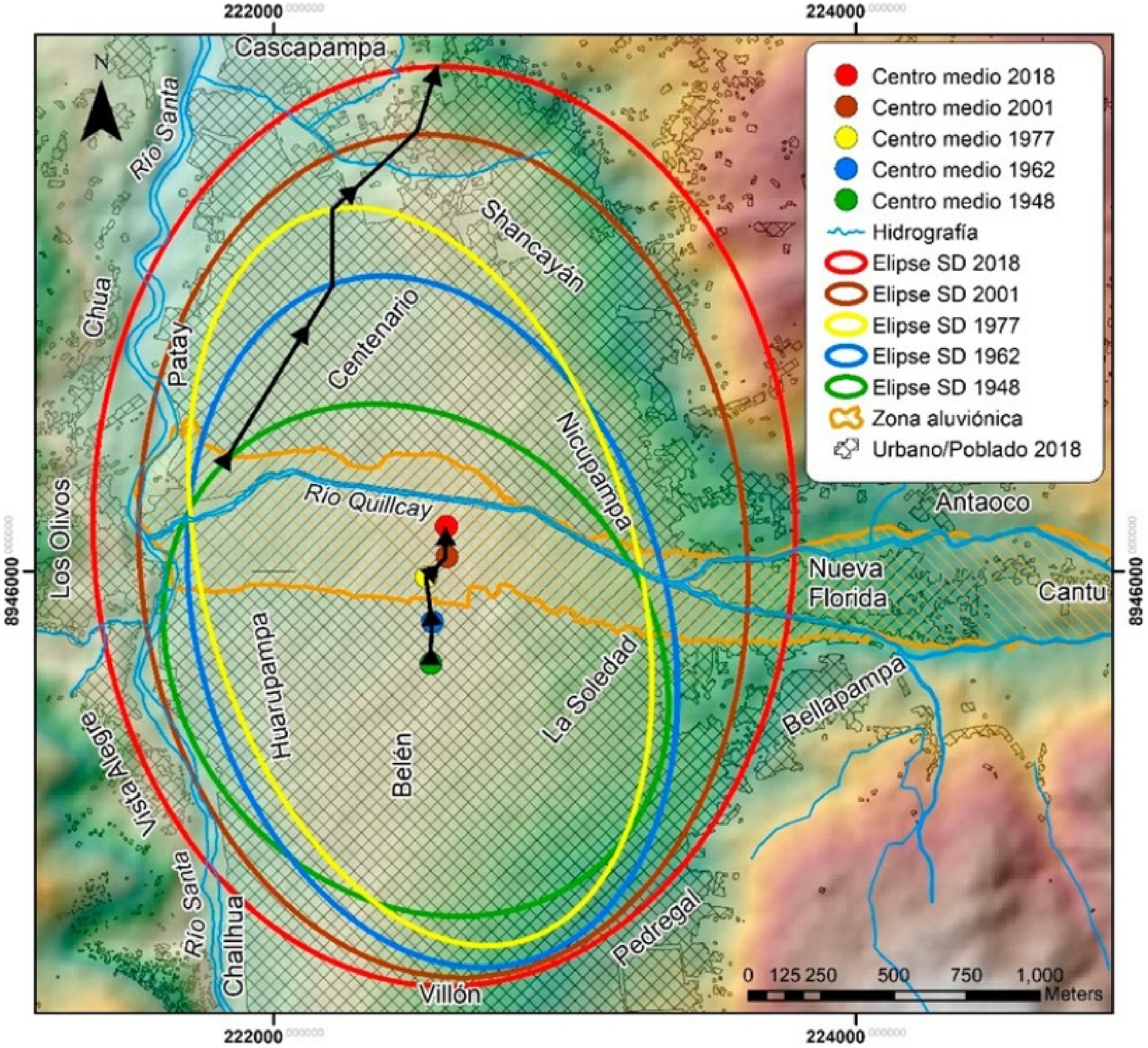


The volume is known for 14% of the lakes while the remaining **86% correspond to small lakes** (average size of 0.03 km²).

Adapted from Munoz et al., (2020).

Discussion | Increasing vulnerability





Villanueva & Vale (2022). Huaraz city growth

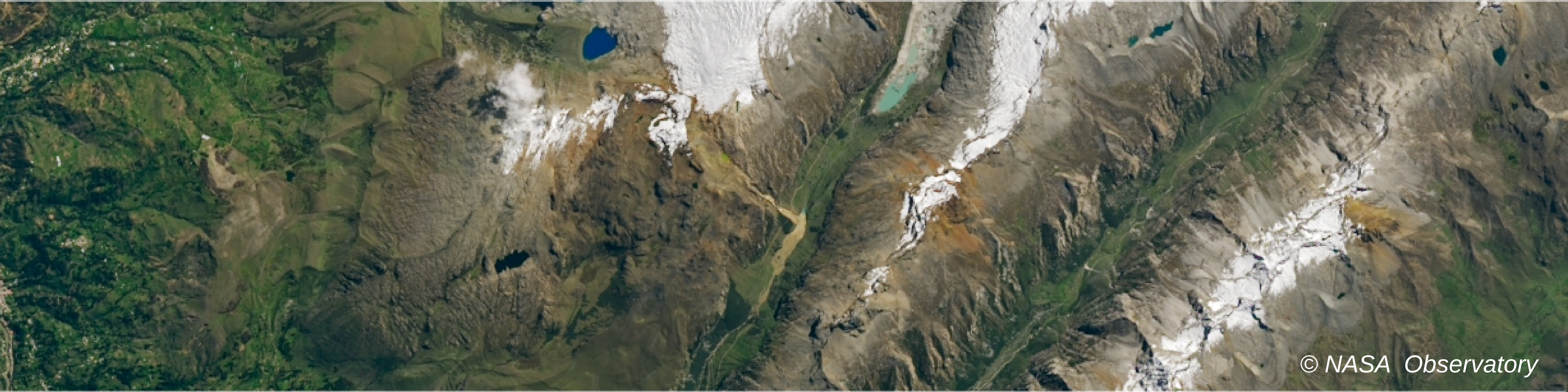
Conclusions

- Regarding the 28 April GLOF:
  - A rock slide of **~270 000 m**^{3} detached from the rockwall.
  - However, **430 000 m**^{3} are totaled in all events.
  - Both lakes A and B make a total volume of **75 000 m**^{3}.
  - Total volume of debris flow that reached Huaraz city was **7 times of the initial volume**.
  - Some precursory events were recorded **3 month before** the 28 April event.

- Small events can (very often ignored) may generate bigger impacts due to cascading effects, notably sediment input.

- Increase in vulnerability. The city of Huaraz is expanding towards the glacial valleys.

April 28, 2025 Vallunaraju GLOF
Insights from high resolution satellite imagery



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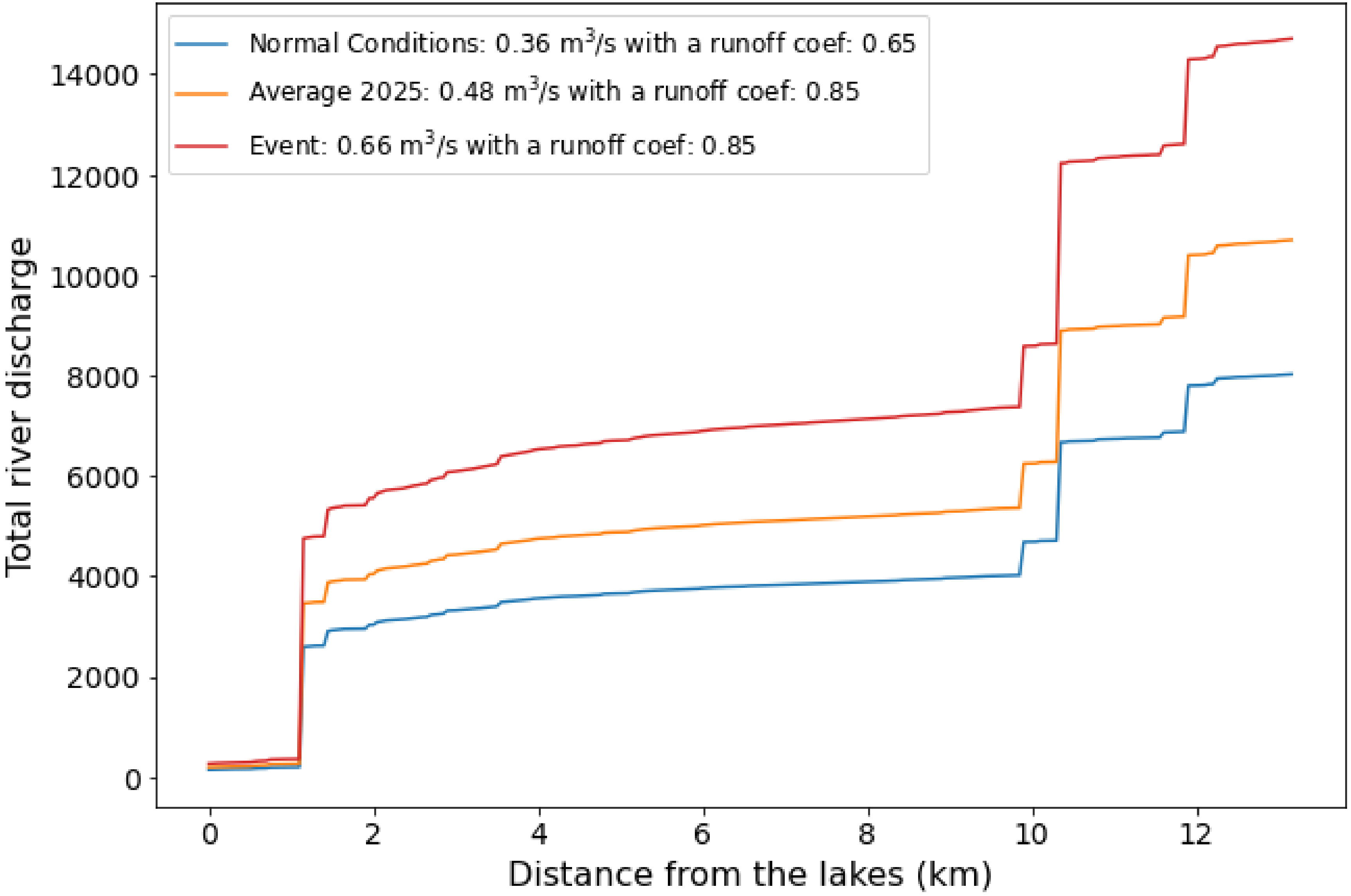
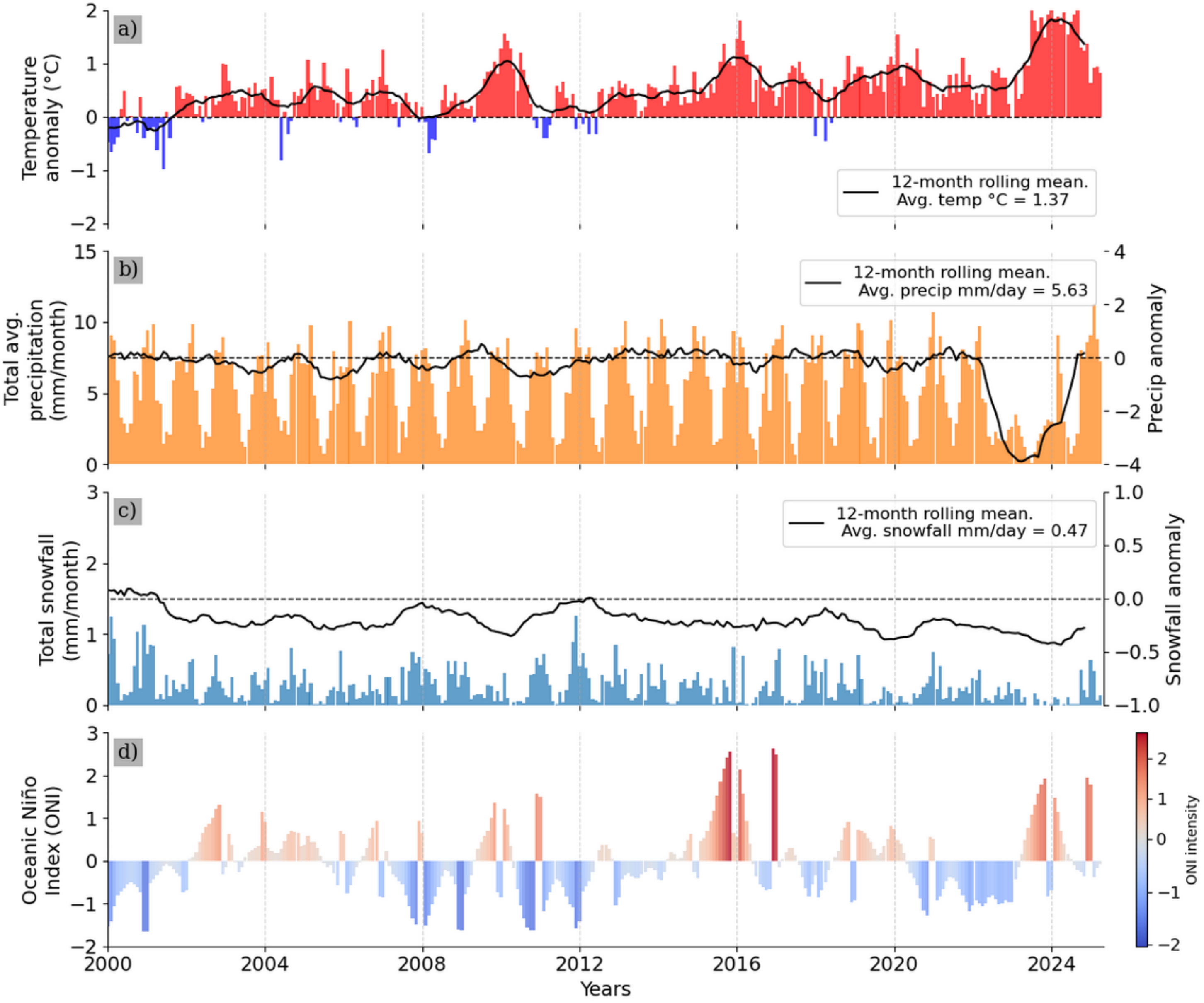
6 Nov, 2025

Results | Discharge analysis



- Initial volume: 75K m^3
- Flood length: 2h
  - Started around 03:30AM
  - First emergency call 05:30AM

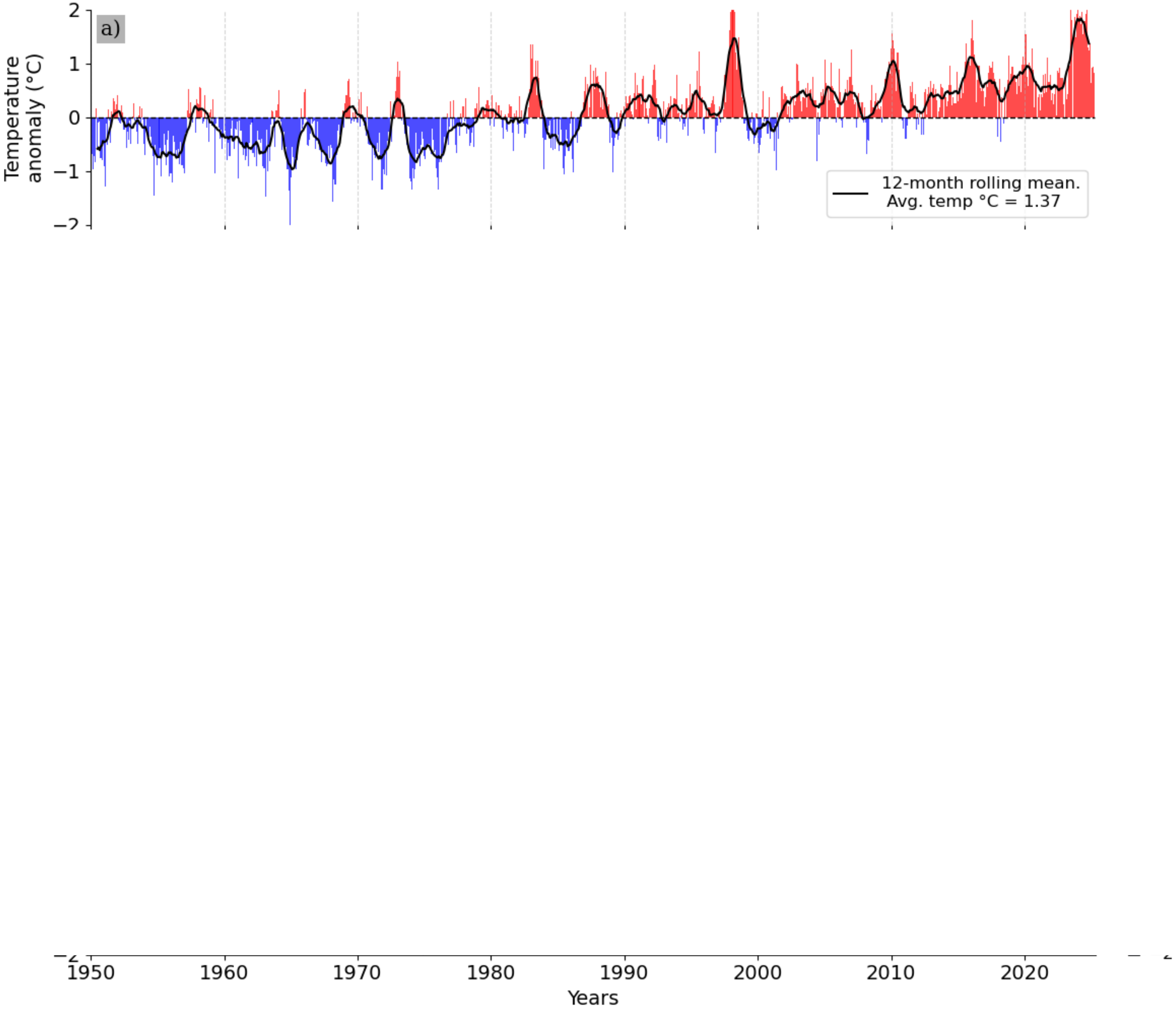
Discussion | Short term weather context (last 25 years)



Effects of ENSO events on mountain slope instabilities?

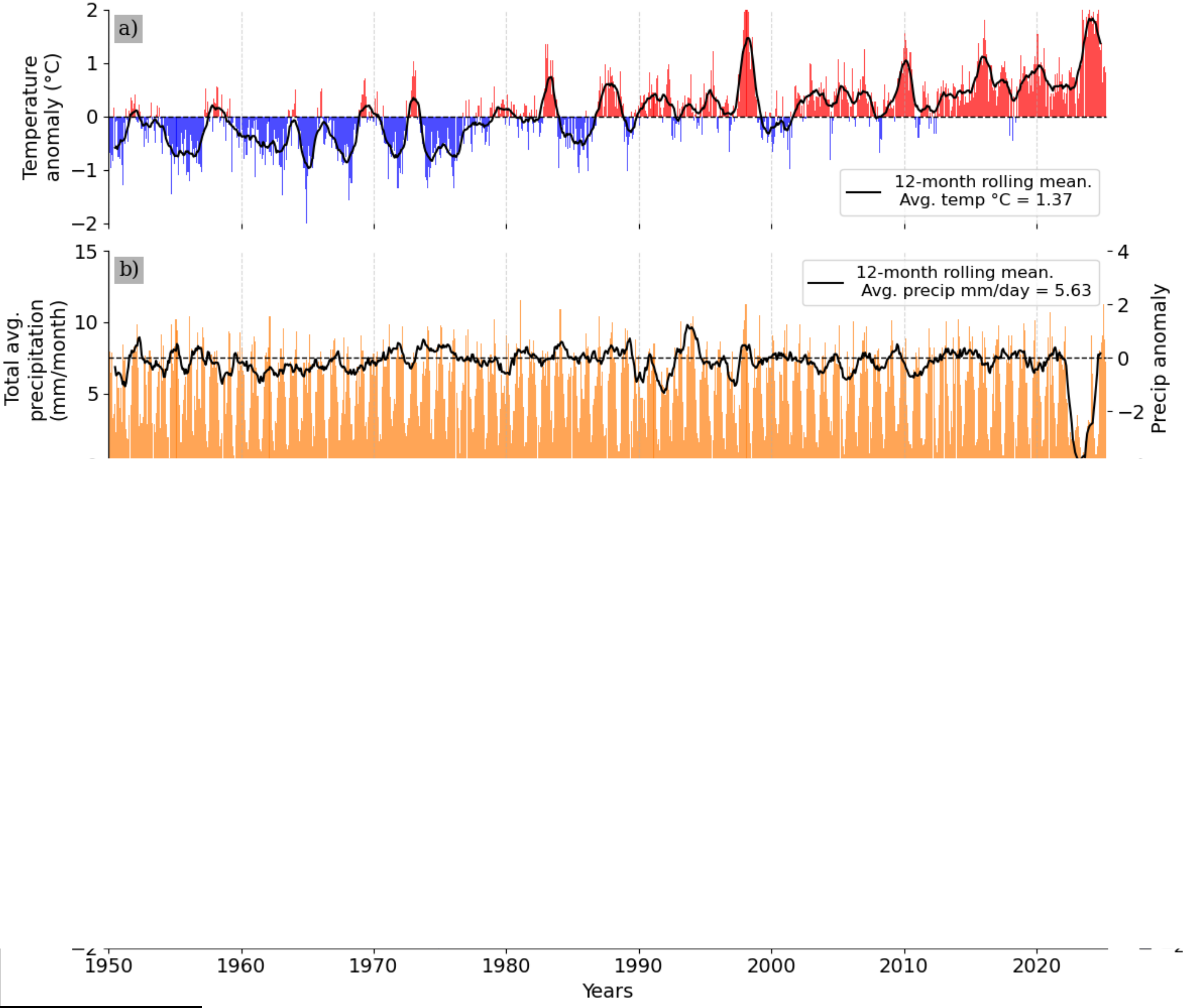
- Less snow = Enhance temperature propagation within the head wall due the less insulation effect during winter.
- Did the temperature anomaly have an influence on permafrost conditions at high altitudes?
- Favored the presence of water inside the rock? Hypothesis to be tested…

Results | Long term weather context (75 years)



Warming at
+0.2°C/decade

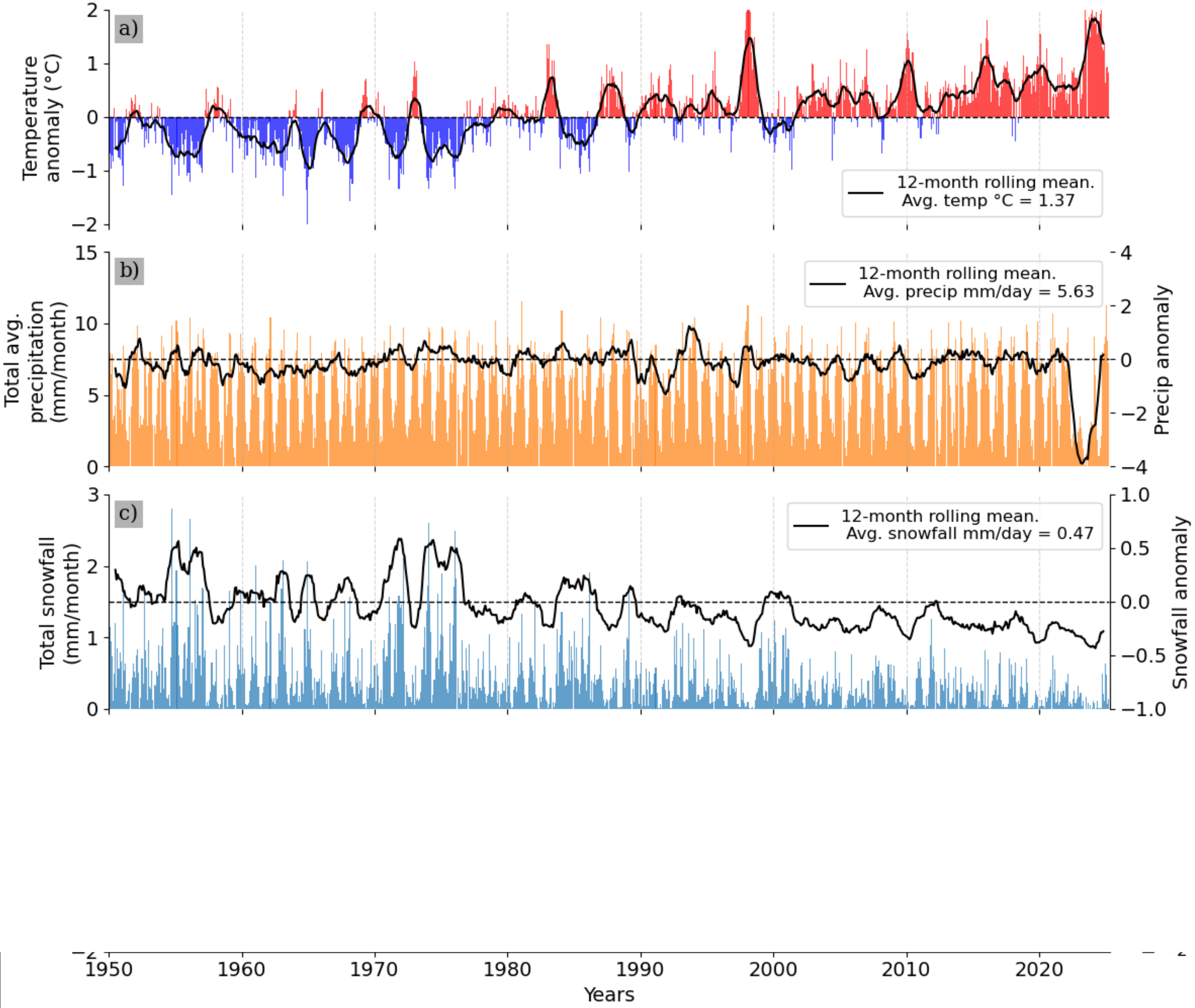
Results | Long term weather context (75 years)



Warming at +0.2°C/decade

No big changes on precipitation outside of 2023 anomaly

Results | Long term weather context (75 years)



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Negative trends on solid precipitation. -0.8 mm/decade

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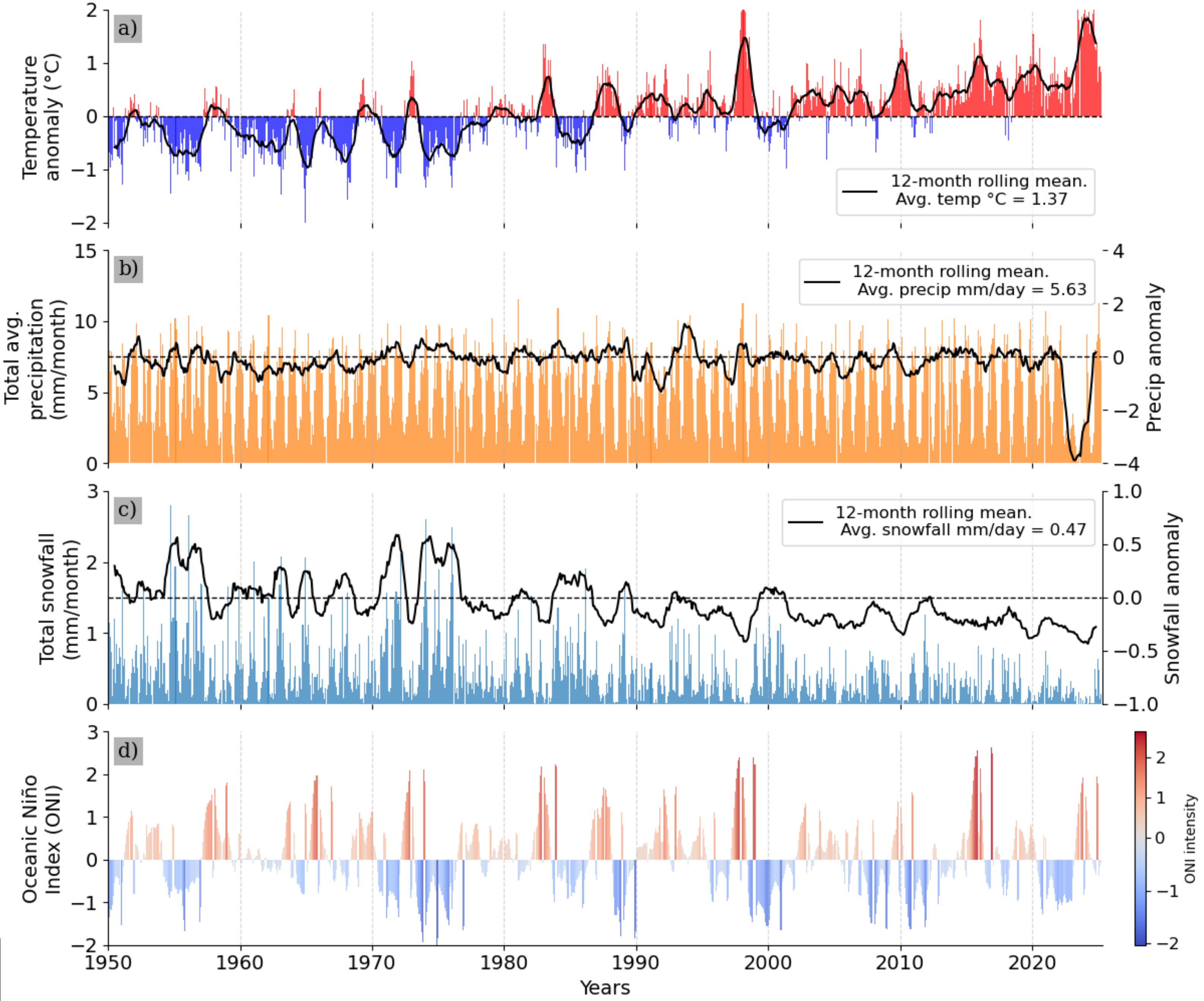

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