

High altitude slope instabilities: detection, monitoring and challenges

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Introduction

High-altitude alpine environments are among the regions most affected by climate change, where glacier retreat, permafrost degradation, and changing precipitation regimes are driving rapid geomorphological change. These interconnected processes increase the occurrence of slope instabilities, landslides, debris flows, and other cascading hazards.

Here, we present case studies demonstrating the complementary use of SAR interferometry and multispectral image analysis to detect and monitor geomorphological changes in alpine environments. We highlight the strengths of different Earth observation datasets for investigating diverse geomorphic processes and discuss key monitoring challenges, including steep topography, adverse weather, and the spatial resolution limits of current satellite sensors, which can hinder the detection of localized processes characteristic of complex alpine landscapes.

Methods

- **DInSAR** → Deformation & displacement
- **Optical / radar offset tracking** → Large & rapid displacement
- **SAR backscatter** → Surface properties & disturbance
- **SAR coherence** → Surface change & instability detection
- **Multispectral analysis** → Vegetation, ground & snow/ice mapping and properties



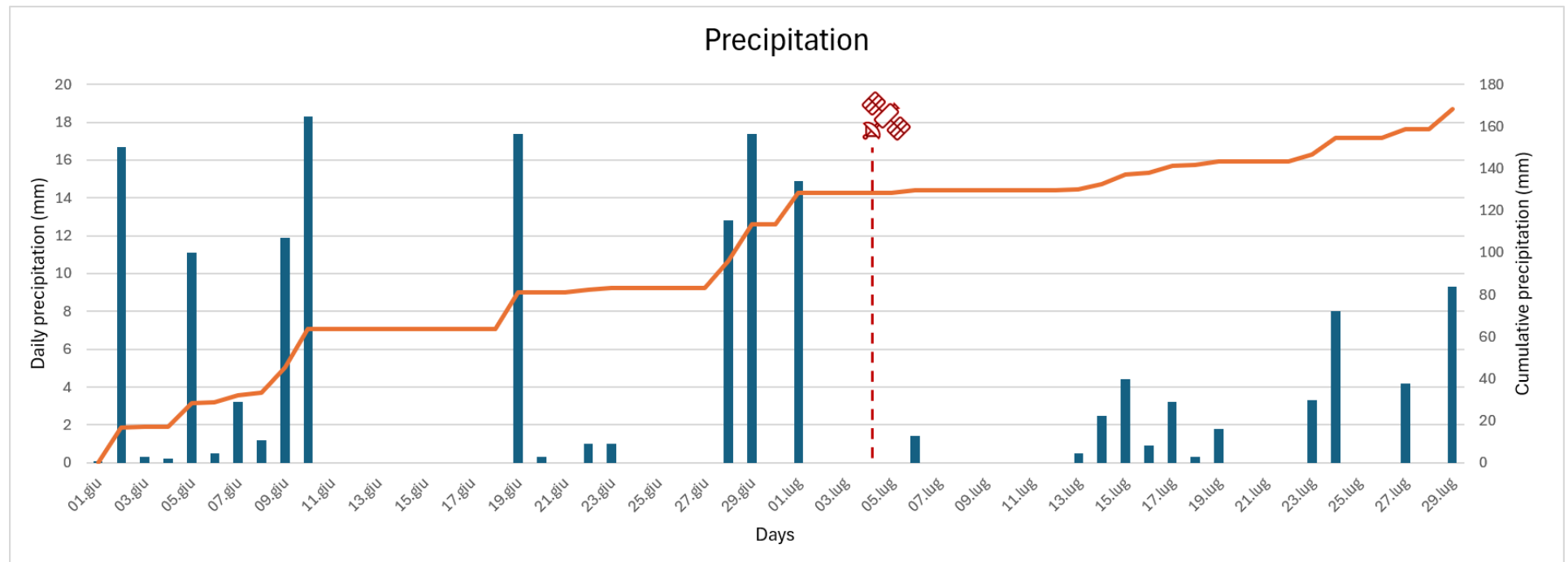
Challenges

- **Complex terrain** → shadows, layover & foreshortening
- **Snow, ice & clouds** → limited visibility and seasonal masking
- **Rapid deformation** → decorrelation, phase aliasing & missed events
- **Heterogeneous surfaces** → difficult detection and classification
- **Limited field data** → challenging validation
- **Spatial & temporal resolution** → too coarse or sparse for local-scale and continuous monitoring

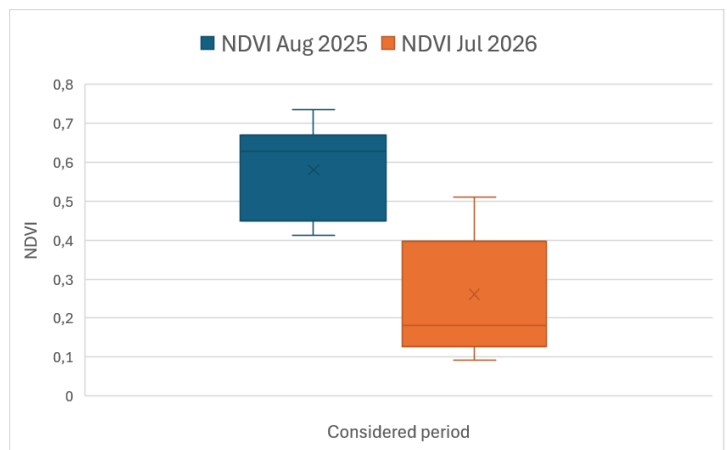
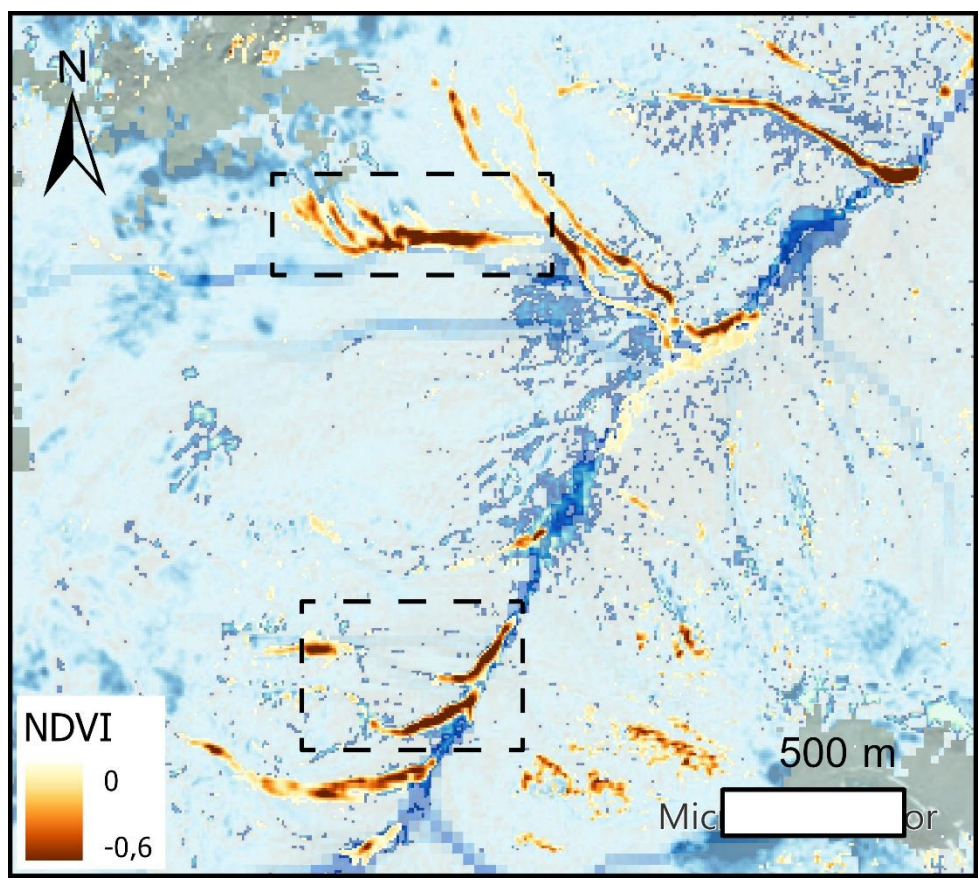
Examples



From current impacts to future sediment sources



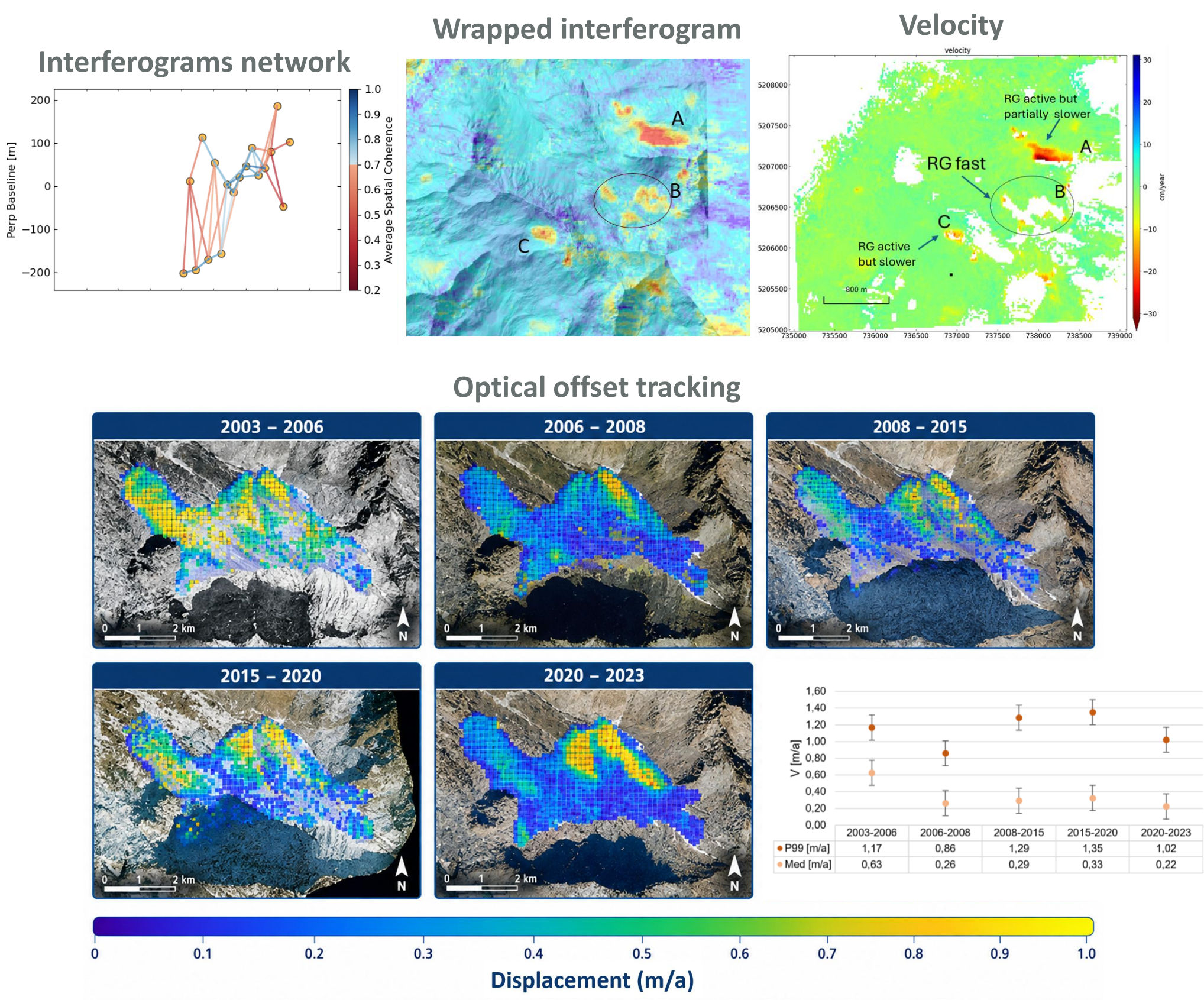
NDVI change from summer 2025 to summer 2026



A summer-to-summer NDVI comparison identifies vegetation loss using a defined threshold. This highlights exposed soil, disturbed surfaces, and tree loss, with particular focus on channel areas. These changes indicate where new, unconsolidated sediment may be available for remobilization, supporting the assessment of potential debris-flow risk. Output: spatial mapping and quantification of newly exposed, potentially mobile sediment contributing to future events.



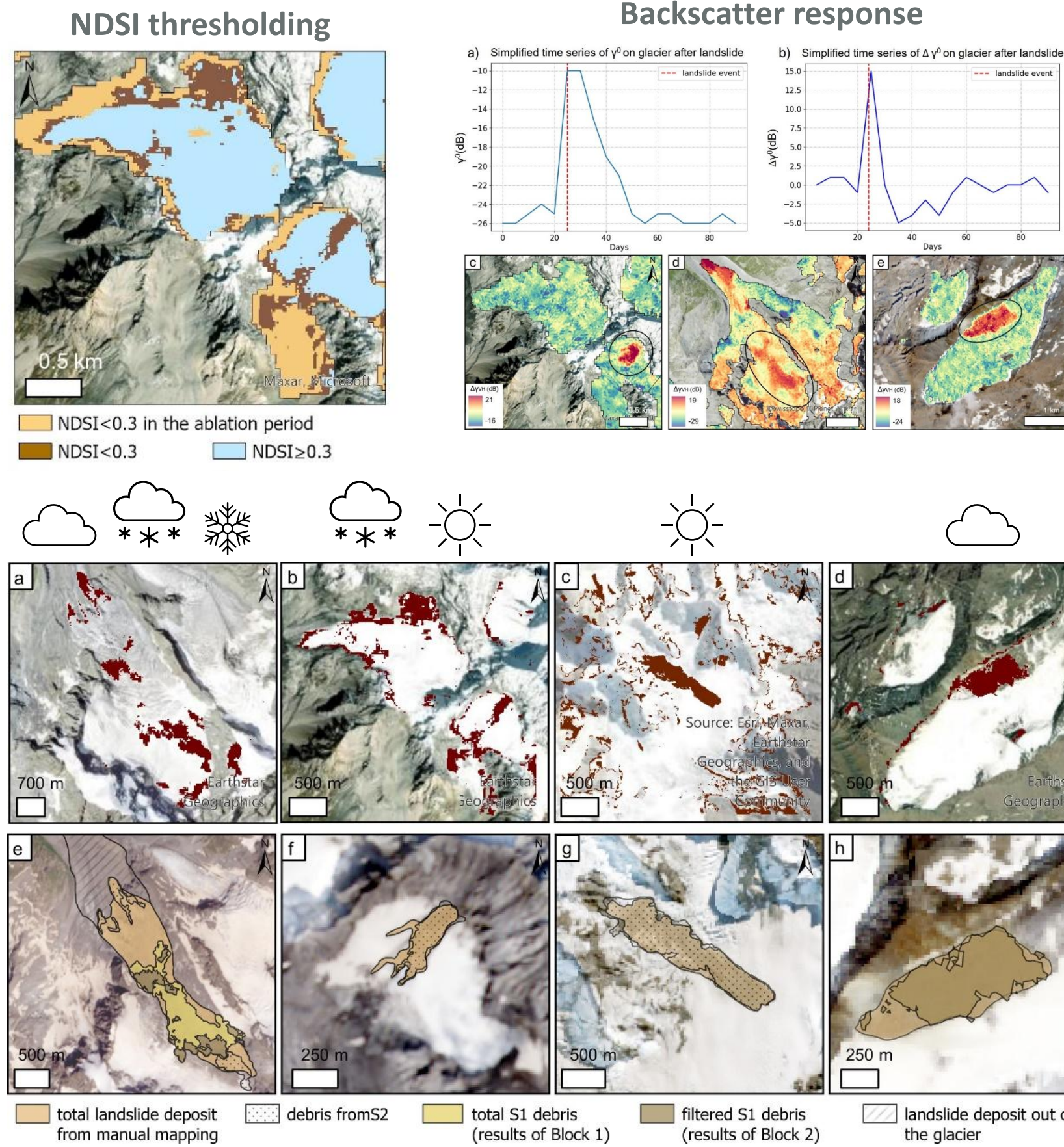
Monitoring ongoing evolution and future instability



SBAS on summer images in 2022–2025 → Noisy signal. Short B_t on Summer 2025 → Less noise, low coherence. High surface velocity and low coherence prevent reliable C-band displacement retrieval, causing phase aliasing and temporal decorrelation and potentially introducing co-registration artefacts. Alternative approach: optical Offset Tracking + CCN. Planet imagery and orthophotos were tested to extract surface displacement and time series, providing a more suitable approach for the rapid dynamics of an active rock glacier in South Tyrol.



Instability, hazard and impacts on glacier condition



Sentinel-2 imagery was used to map snow and ice (NDSI > 0.3) and identify potential debris-covered areas, while excluding consistently exposed rock. Cloud-related gaps were complemented with Sentinel-1 backscatter time series. Filtering based on clusters, $\Delta\gamma^0$, temporal trends, and previous hydrological years retained only significant surface changes, such as landslides. The results showed up to 90% overlap with manually mapped deposits for immediate post-event mapping, and 50% where mapping was delayed by snow and clouds. The workflow uses open-source data and tools and can be transferred to other glacial environments.