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Using historical aerial imagery to assess multidecadal kinematics and elevation changes. Application to mountain permafrost in the French Alps.

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Glacial and periglacial environments are highly sensitive to climate change, even more in mountain areas where warming is faster and, as a consequence, perennial features of the cryosphere like glaciers and permafrost have been fast evolving in the last decades. In the European Alps, glaciers retreat and permafrost thawing have led to the destabilization of mountain slopes, threatening human infrastructures and inhabitants. The observation of such changes at decadal scales is often limited to sparse in situ observations.

Here, we present three study cases of mountain permafrost sites based on a multidisciplinary approach over almost seven decades. The goal is to investigate and quantify morphodynamic changes and understand the causes of these evolutions. We used stereo-photogrammetry techniques to generate orthophotos and (DEMs) from historical aerial images (available, in France since 1940s). From this, we produced diachronic comparison of DEMs to quantify vertical surface changes, as well as feature tracking techniques of multi-temporal digital orthophotos for estimating horizontal displacement rates. Locally, high-resolution datasets (i.e. LiDAR surveys, UAV acquisitions and Pléiades stereo imagery) were also exploited to improve the quality of photogrammetric products. In addition, we combine these results with geophysics (ERT and GPR) to estimate the ice content, geomorphological surveys to describe the complex environments and the relationship with climatic forcing.

The first study case is the Laurichard rock glacier, where we were able to quantify changes of emergence velocities, fluxes, and volume. Together with an acceleration of surface velocity, important surface lowering have been found over the period 1952-2019, with a striking spatiotemporal reversal of volume balance.

The second study site is the Tignes glacial and periglacial complex, where the changes of thermokarstic lakes surface were quantified. The results suggest that drainage probably affects the presence and the evolution of the largest thermorkarst. Here too, a significant ice loss was

found on the central channel concomitant to an increase in surface velocities.

The third study site is the Chauvet glacial and periglacial complex where several historical outburst floods are recorded during the 20th century, likely related to the permafrost degradation, the presence of thermokarstic lakes, and an intra-glacial channel. The lateral convergence of ice flow, due to the terrain subsidence caused by the intense melting, may cause the closure of the channel with a subsequent refill of the thermokarstic depression and finally a new catastrophic event.

Our results highlight the important value of historical aerial photography for having a longer perspective on the evolution of the high mountain cryosphere, thanks to accurate quantification of pluri-annual changes of volume and surface velocity. For instance, we could evidence : (1) a speed-up of the horizontal displacements since the 1990s in comparison with the previous decades; (2) an important surface lowering related to various melting processes (ice-core, thermokarst) for the three study sites; (3) relationships between the observed evolution and the contemporaneous climate warming, with a long-term evolution controlled by the warming of the ground and short-term changes that may relate to snow or precipitation or to the activity of the glacial-periglacial landforms.