Geophysical Research Abstracts
Vol. 17, EGU2015-14687, 2015
EGU General Assembly 2015

Spatial patterns of rockfall in recently deglaciated high-alpine rock faces: Analysing rockfall release zones and volumes based on a multiannual LiDAR time series, Kitzsteinhorn, Austria.

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Rock instabilities in high-alpine areas represent a considerable risk factor for man and infrastructure. In the Alps numerous, mainly visual, observations suggest an increasing occurrence of rockfall events potentially associated to climate warming. However, unbiased high-precision information on the location of rockfall release zones and the size of event volumes is scarce. Thus, frequency/magnitude patterns of high-alpine rockfall often remain elusive. The presented study addresses the need for systematically acquired, objective field data by presenting an extensive, multiannual LiDAR time series from a high-alpine (peri)glacial environment.

The study area is located in the summit region of the Kitzsteinhorn (3.203 m), Hohe Tauern Range, Austria. The beginning of the terrestrial laserscanning (TLS) monitoring campaign dates back to July 2011. Since then six rock faces have been scanned repeatedly at an interval of 1-2 months during the snow-free summer season (June to October). The investigated rock faces predominantly consist of calcareous mica-schist and differ in terms of height, slope, aspect, and discontinuity orientation. The rock faces are partially underlain by permafrost, their combined surface area is approx. 1.3 km^2. They are located directly adjacent to the Schmiedingerkees cirque glacier, which has retreated and thinned significantly in recent decades (downwasting rate $\sim$1.5 m/a).

TLS data acquisition was performed using a Riegl LMS-Z620i. During data acquisition no permanently fixed installations and no artificial reflective markers were used. This is in line with the requirement to develop a quick, flexible methodology that can be applied not only at the Kitzsteinhorn, but also in other, similar environments. For data post-processing a new analysis procedure has been developed which allows (i) point cloud alignment by surface geometry matching, (ii) objective, automated discrimination between measurement errors und real surface changes, and (iii) calculation of uncertainty statistics.

From 2009 until 2014 over 100 rockfall release zones have been detected. All rockfall events combined amount to a total volume of approx. 5000 m^3. Two thirds of the detected rockfall release zones possess volumes < 10 m^3. About one tenth of the detected rockfall release zones display volumes larger than 100 m^3. The spatial distribution of the rockfall release zones displays a distinct pattern: 54% of the detected rockfall release zones are located < 15 m from the glacier surface, another 24% are located between 15-30 m from the glacier surface. Not counting one strongly deviating extreme event (2400 m^3 rockfall reconstructed from ALS data) the distribution of rockfall volumes displays a remarkably similar pattern: 56% of the total rockfall volume was triggered from areas located < 15 m from the glacier surface, 23% of the total volume stems from release zones located 15-30 m from the glacier surface. Thus, areas that have been exposed over the last 1-2 decades by the thinning of the Schmiedingerkees are particularly likely to be affected by rockfall.