20-year permafrost evolution documented through petrophysical joint inversion, thermal and hydrological data

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This study investigates the ground characteristics of the high altitude (3’410 m a.s.l.) permafrost site Stockhorn in the Swiss Alps using a combination of surface and subsurface temperature, soil moisture, electrical resistivity and P-wave velocity time series data including a novel approach to explicitly quantify changes in ground ice content. This was motivated by the clear signal of permafrost degradation visible in the full available dataset at this long-term monitoring site within the PERMOS (Permafrost Monitoring Switzerland) network. First, we assess the temporal and spatial evolution of the ground ice and water content by combining and analysing all available in situ thermal (borehole and ground surface temperature), hydrological (soil moisture) and geophysical (geoelectric and seismic refraction) data over two decades (2002-2022) regarding the driving factors for the spatially different warming. Secondly, we explicitly quantify the volumetric water and ice content and their changes in the subsurface from 2015 to 2022 using a time-consistent petrophysical joint inversion scheme using the open-source library pyGIMLi. The petrophysical joint inversion scheme has been improved by constraining the rock content to be constant in time for six subsequent inversions. This allows us to obtain consistent changes in ice and water content over the monitoring period based on jointly inverted resistivity and traveltime data. All the different data show a warming trend of the permafrost. The ice content calculated from the petrophysical joint inversion has decreased by about 15 vol.% between 2015 and 2022. Changes in ice content are first observed in the lower, south-facing part of the profile. As a result, resistivity and P-wave velocity have been decreasing significantly. Permafrost temperatures measured in the boreholes have increased between 0.5 and 1°C in 20 years. Our study shows the high value of joint and quantitative analysis of datasets comprising complementary subsurface variables for long-term permafrost monitoring.