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Understanding the response of very small glaciers in the Swiss Alps to climate change

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Very small glaciers (<0.5 km^2) are omnipresent in mid- to low-latitude mountain ranges worldwide and typically account for approximately 80% of the total number of glaciers. Although their total area and volume is small compared to larger glaciers, they are a relevant component of the cryosphere. Very small glaciers influence the runoff regime in poorly glacierized catchments, contribute to landscape formation in cirques, can be the origin of natural hazards and are not negligible for current sea-level rise. Further, they are of economic interest to winter tourism resorts, can be used to study historical to Holocene climate conditions or to predictlocations wherearchaeological remains can potentially be found due to ongoing glacier melt.

Alpine glacier research has traditionally focussed on medium- to large-sized valley glaciers. Empiric data and studies focussing on very small glaciers are sparse.Depending on the relative influence of regional climate conditions, local topography, debris cover and permafrost, the smallest glaciers typically show highest variability in their morphogenetic setting and glacier dynamics. Because small-scale processes, complex feedbacks and non-linearities govern their past and future evolution, assessing very small glacier response at the regional scale to climate change is challenging and only feasible if backed up with comprehensive field data.In general, our understanding about the sensitivity and response of very small glaciers to climate change is still very limited.

This PhD thesis aimed to close this knowledge gap for the Swiss Alps. Together with existing data, new in-situ measurements for mass balance, ice thickness distribution, surface velocity and temperature regime were collected on selected glaciers across the Swiss Alps to gauge the current state of very small glaciers. Moreover, the application and validation of long-range terrestrial laser scanning to monitor the annual surface elevation and mass changes of dwarf glaciers was tested.The recent glacierization in Switzerland was determined based on the compilation of a new glacier inventory (SGI2010). Three-dimensional changes of all Swiss glaciers over the past decades were investigated by comparing consecutive glacier outlines and digital terrain information from around 1980 and 2010. The sensitivity and response of very small glaciers in the Swiss Alps to climate change was assessed by calibration of a glacier evolution model to the observed individual glacier volume changes and validated against glacier-wide seasonal mass balance, ice thickness and englacial temperature data from in-situ measurements. Results of all studies are accompanied with in-depth uncertainty assessments.

More than 1100 individual glaciers smaller than 0.5km^2 (82% of the total number of glaciers) still existed in the Swiss Alps in 2010. 733 glaciers (34% of the total number) completely vanished between 1973 and 2010.Around 2010, mean ice thickness was 19m on average, horizontal ice surface velocities typically on the order of a few metres yr^{-1}. Many very small glaciers currently exhibit a polythermal temperature regime and about one third are at least partially debris covered. Compared to larger glaciers, the whole sample of predominantly climatic-controlled dwarf glaciers in Switzerland showed a similar average sensitivity and response to climatic changes. However, area and mass changes were most variable, pointing out the strikingly individual response of very small glaciers to a similar regional climate forcing.Relative to 2010, the large majority of very small glaciers in the Swiss Alps will have completely disappeared by the middle of the 21st century. Some small and steep glaciers <0.5km^2 situated at high elevation and a few highly topographic-controlled avalanche-fed glaciers at low elevation might survive even under substantial warming. Together with the monitoring approach promoted in this thesis, terrestrial laser scanning techniques are promising to derive repeated annual geodetic mass balances of very small glaciers. Respective results and uncertainty were in close agreement with direct glaciological mass balances extrapolated from dense in-situ measurements.

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