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Abstract

Snow regimes in high-mountain regions are changing in response to atmospheric warming. However, the scarcity and limited accuracy of observations of snow and precipitation at high elevation reduce our understanding of cryosphere-climate linkage. Here, we compare the winter mass balance of 95 glaciers distributed over the Alps, Western Canada, Central Asia and Scandinavia, with the total precipitation from the ERA-5 and the MERRA-2 reanalysis products during the snow accumulation seasons from 1981 until today. We propose a machine learning model to adjust the precipitation of reanalysis products to the elevation of the glaciers, thus deriving snow water equivalent (SWE) estimates over glaciers uncovered by ground observations and/or filling observational gaps. We use a gradient boosting regressor (GBR), which combines several meteorological variables from the reanalyses (e.g. air temperature, relative humidity) with topographical parameters. These GBR-derived estimates are evaluated against the winter mass balance data by means of a leave-one-glacier-out cross-validation (site-independent GBR) and a leave-one-season-out cross-validation (season-independent GBR). The GBRs allowed to reduce (increase) the bias (correlation) between the precipitation of the original reanalyses and the winter mass balance data of the glaciers (from an overall RMSEs (CORR) of 946 mm (0.74) and 793 mm (0.81) of MERRA-2 and ERA-5, to 443 mm (0.85) and 422 mm (0.86) of the site-independent GBRs, and 287 mm (0.94) and 272 mm (0.95) of the season-independent GBRs). Finally, the GBR models are used to derive SWE trends on glaciers between 1981 and 2021. The resulting trends are more pronounced than those obtained from the total precipitation of the original reanalyses. On a regional scale, significant 41-year SWE trends are observed in the Alps (MERRA-2 season-independent GBR: +0.4 %/year) and in Western Canada (ERA-5 season-independent GBR: +0.2 %/year), while significant positive/negative trends are observed in all the regions for single glaciers or specific elevations. Negative (positive) SWE trends are typically observed at lower (higher) elevations, where the impact of rising temperatures is more (less) dominant. However, denser ground-based or improved remote sensing observations would enable to further evaluate and develop the presented methods. In future research, we thus aim at exploiting snow depth observations derived from the novel ICESat-2 satellite laser altimeter to improve the reliability of machine learning model-based snow estimates in high-mountain observation-scarce regions.