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A data-fusion approach towards continuous spatio-temporal snow water equivalent in high-mountain regions

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Accurate knowledge of precipitation and snow distribution in high-mountain regions is crucial for hydrology, glaciology, climatology, water resources and natural hazard studies. Climate change has significantly impacted the high-mountain cryosphere, and understanding precipitation patterns is essential for assessing these changes. However, precipitation trends with elevation remain unclear. A major source of uncertainty is the limited spatial and temporal coverage of ground-based observations in high-mountain regions. Snow water equivalent (SWE) observations, which measure the water content in the snowpack, are also sparse but can be obtained from glacier monitoring. SWE measurements on glaciers are thus typically the only few direct ground observations that can represent precipitation at high elevations. Remote sensing observations, numerical weather models and reanalyses can also provide useful information on precipitation and SWE. However, their coarse resolution limits their reliability in complex terrain. Thus, this thesis aims at (1) quantifying precipitation biases at high elevation by exploiting SWE observations on glaciers and (2) developing data-driven methods to provide continuous SWE estimates from local to global scale, by fusing different data sources.

First, three gridded precipitation products for high-mountain regions are evaluated using reliable daily SWE measured by cosmic ray sensors on two Swiss glaciers. The results show a large bias in all precipitation products at monthly and seasonal resolutions, with varying performance depending on in situ wind direction during snowfall events.

Second, a multiple linear regression is used to generate continuous spatio-temporal SWE estimates on eight Swiss glaciers. High-resolution topographical information are found to be important for explaining preferential deposition processes at small spatial scales. The potential use of the model is also tested on non-glacierized sites, showing limitations due to their more complex topography compared to glaciers.

Third, SWE (winter mass balance data) on 95 glaciers in the European Alps, Scandinavia, Central Asia and western Canada is used to train a gradient boosting regressor (GBR) model that aims at adjusting the precipitation biases of reanalysis products against SWE on glaciers. The most important variables used by the GBR models are those related to the elevation difference between the glacier surface and the terrain model underlying the reanalyses. The results indicate that filling temporal data gaps is simpler than estimating SWE on glaciers where no in situ observations are available. The GBR models also show improved performance in reproducing temporal changes of SWE (over years) than reanalyses, potentially providing insights on the relation between climate change and snow accumulation over glaciers.

Finally, a combined data-assimilation and deep-learning approach is used to obtain continuous spatio-temporal SWE estimates, learning from SWE derived from photogrammetric snow depth along ground tracks that mimic observations from satellite-borne lidars, such as ICESat-2. The study is developed in Switzerland, but the data/methods are available/can be used worldwide. A sensitivity test enhances limitations and perspectives towards the use of the approach with real ICESat-2 observations, i.e., towards a potential worldwide application.

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