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Detailed comparison of the geodetic and direct glaciological mass balances on an annual time scale at Hintereisferner, Austria

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The quantification of glacier mass changes is fundamental for glacier monitoring and provides important information for climate change assessments, hydrological applications and sea-level changes.
On Alpine glaciers two methods of measuring glacier mass changes are widely applied: the direct glaciological method and the geodetic method. Over the last decades several studies compared the mass balance estimates obtained by both methods to identify and correct stochastic and systematic errors. In almost all of these studies, the time span for comparison between the two methods is about one decade or longer.
On Hintereisferner (HEF; Ötztal Alps, Austria) mass balance measurements were initiated in the glaciological year 1952/53, resulting in a consistent mass balance data set with an estimated accuracy of ±0.2 m w.e. a-1. Furthermore, 11 airborne laser scanning (ALS) campaigns were conducted between 2001 and 2011 at HEF, all consistent in accuracy as well as in precision (± 0.04 to 0.10 m for slopes ≤ 50°). This is a world-wide unique ALS dataset of a glacierized alpine catchment. Flight campaigns were performed close to the end of the hydrological year (30th September). Resulting data provide high quality topographic information to derive glacier mass changes by applying the geodetic method. On sub-decadal time-scales such method comparisons are rare, or reveal unexplainable large discrepancies between both mass balance methods. In this study we estimate stochastic and systematic uncertainties of the ALS data for processing volume changes, and quantify methodological differences, such as density assumptions, unequal measurement dates, crevasses and glacier dynamics. Hence, we present a method to compare direct glaciological and geodetic mass balances on an annual basis.
In a first step, we calculate the annual geodetic mass balance of HEF between 2001 and 2011, resulting in a thickness change map of the glacier. In a second step, the snow cover, which has eventually built up before the ALS acquisition, is corrected. As snow cover biases are particular uncertain, a statistical approach has been applied to assess combined DTM errors by using the population of DTM differences over stable terrain. This method incorporates all known and unknown error sources from the surface difference in stable areas and uses its median thickness for correction in all altitudinal belts. In addition, intensity data of the ALS surveys are used to classify the optical surface properties into ice and firn zones. The resulting grids with according conversion factors (900 and 700 kg/m^3 for ice and firn, respectively) are combined to calculate mass changes. In a last step, the survey dates are adjusted, using numerous field observations.
On an annual time scale, the geodetic mass balances of HEF corrected using this approach, correlate well with the results from the homogenized direct glaciological method. Significant deviations occur in years with few measurements in the uppermost areas applying the direct glaciological method, due to strong melt in areas not equipped with ablation stakes (cf. Figure 2 for 2002/03) or inaccessibility due to weather conditions. On the basis of these results, the conventional error risk (e.g. confidence levels), was adopted in order to test the null hypothesis and to check if unexplained discrepancies suggest reanalyses of glaciological mass balances.
Regarding the cumulative mass balance, the deviations between the two methods tend to become smaller the longer the period of comparison extends. Averaged between 2001 and 2011 the largest sources of differences are snow cover and density assumptions having high uncertainties in their estimates and/or leading to higher error ranges in the geodetic mass balances. Some errors were found to have a minor impact and are not treated explicitly, such as uncertainties in different glacier outlines used in both methods or the influence of snow covered and snow free crevasses in successive years on the geodetic mass balance.