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A reanalysis of one decade of the mass balance series on Hintereisferner, Ötztal Alps, Austria: a detailed view into annual geodetic and glaciological observations

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Abstract. This study presents a reanalysis of the glaciologically obtained 2001–11 annual glacier mass balances record at Hintereisferner, Ötztal Alps, Austria. The reanalysis is accomplished through a comparison with geodetically derived mass changes, using annual high-resolution airborne laser scanning (ALS). The grid based adjustments for the method-inherent differences are discussed along with associated uncertainties and discrepancies of the two forms of mass balance measurements. A statistical comparison of the two datasets shows no significant difference for seven annual as well as the cumulative mass changes over the ten years record. Yet, the statistical view hides significant differences in the mass balance years 2002/03 (glaciological minus geodetic records = +0.92 m w.e.), 2005/06 (+0.60 m w.e.) and 2006/07 (–0.45 m w.e.). The validity of the results is critically assessed and concludes that exceptional atmospheric circumstances can render the usual glaciological observational network inadequate. Furthermore, we consider that ALS data reliably reproduce the annual mass balance and can be seen as calibration tools of or, under certain circumstances, even as a substitute for the glaciological method.

1 Introduction

The mass balance of a glacier defines its hydrological reservoir function (e.g. Kaser et al., 2010) and is a high-confidence indicator of climate change (e.g, Vaughan et al., 2013; Bojinski et al., 2014). There are two primary methods for determining the mass balance of a glacier. The glaciological method is the most widely used for assessing annual and – more rarely – seasonal mass changes of individual glaciers (e.g. Anonymous, 1969; Hoinkes, 1970; Kaser et al., 2003; Cogley et al., 2011). It spatially extrapolates in situ point measurements of ablation and accumulation to the glacier-wide surface mass balance, encompassing changes at the glacier surface (Cogley et al., 2011). Earliest glacier mass balance measurements started around 1950, but only about 30 reference glaciers have uninterrupted annual time series going back to 1976 (e.g. Zemp et al. 2009). This small number of annually measured glacier mass balance series provides the basis for reconstructing past contributions to sea level rise (e.g. Kaser et al., 2006; Marzeion et al., 2012; Gardner et al., 2013; Vaughan et al., 2013), extrapolating glaciers' contribution to regional water supply (e.g. Kaser et al., 2010, Weber et al., 2010, Huss, 2011, Bliss et al. 2014), and glacier change detection, attribution (Marzeion et al., 2014; Slangen et al., 2016) and projection studies (e.g. Radić and Hock, 2006; Marzeion et al., 2012; Radić et al., 2013; Huss and Hock, 2015; Mengel et al., 2016).

The surface mass balance is defined as the mass change at the glacier surface and within the snow cover which evolves during the balance year (cf. Cogley et al. 2011). In contrast to the surface mass balance obtained with the glaciological method, the geodetic method subtracts two consecutive digital terrain models (DTMs) of a glacier and provides its volume change. This method integrates over all processes that lead to surface height changes at any single point of a glacier, i.e. the surface, internal, and basal mass changes as well as those from ice flux divergence, and densification (Cuffey and Paterson, 2010). Consequently, the mass balance values at a certain point of the glacier may differ significantly between the glaciological and the geodetic mass balance method. However, according to the principals of mass conservation, the ice flux divergence becomes zero if integrated over an entire glacier Moreover, by assuming internal and basal mass changes on mid latitude mountain glaciers to be of minor importance (e.g Cuffey and Paterson, 2010), and by applying either measured or estimated snow or ice density to convert volume into mass changes, the two methods should obtain fairly similar numbers for the total mass balance. In this way, geodetically obtained results have been used as controls for annual glaciological mass balances at decadal scales and are commonly applied to identify random and to correct systematic uncertainties in glaciological mass balance time series (Hoinkes, 1970; Haeberli, 1998; Fountain et al., 1999; Krimmel, 1999; Østrem and Haakensen, 1999, Hagg et al. 2004; Cox and March, 2004, Huss et al., 2009; Thibert and Vincent, 2009; Koblet et al., 2010; Zemp et al., 2010; Prinz et al., 2011; Zemp et al., 2013; Galos et al., 2017). Geodetic measurements have also been merged with glaciological mass balance series to increase coverage and representativeness of large regions' and global glacier mass balance information (e.g. Cogley 2009; Gardner et al., 2013). Indeed, the interconnection of different methods is increasingly suggested in order to ensure progress in glacier mass change estimates for large regions or even on the global scale (Gardner et al., 2013; Marzeion et al., 2017).

At Hintereisferner in the Austrian Ötztal Alps, glaciological and photogrammetry based geodetic mass balances are available since the early 1950s (e.g. Kuhn et al., 1999). Early analyses showed good agreement between the two data series on a decadal time scale for the periods 1952/53 to 1963/64 (Lang and Patzelt, 1971) and 1952/53 to 1990/91 (Kuhn et al., 1999). Yet, a more detailed examination by Zemp et al. (2013) revealed discrepancies at Hintereisferner for the periods 1963/64 to 1968/69 and 1978/79 to 1990/91.

Geodetic mass balances for Hintereisferner were obtained at annual time steps between 2001 and 2011, when high resolution air borne laser scanning (ALS) became available. Gross results from the first data pairs indicated considerable differences to the glaciological mass balances (Geist and Stötter, 2007). These differences and the meanwhile available 11 annual high-quality ALS-data sets motivate and enable a so far unique validation and, finally, a reanalysis of annual surface mass balances of a glacier.

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This study presents the first use of annual geodetic records for a detailed reanalysis of an annual glaciological mass balance record. This is achieved by a stepwise assessment of method-inherent uncertainties in each dataset (σ; section 3) and the accounting for method-inherent differences (ε) between the surface (glaciological) and the total (geodetic) mass balance (section 4). In section 5 we thoroughly perform and discuss the final reanalysis of the glaciological record, ending with concluding remarks in section 6.

2 Hintereisferner

Hintereisferner (46.79°N, 10.74°E) is a valley glacier in the Austrian part of the Ötztal Alps (Figure 1). The glacier consists of three main tributary basins. Langtaufererjochferner (1.11 km²) and Stationsferner (0.28 km²) disconnected from Hintereisferner in 1969 and 2000, respectively, but are still treated as part of the glacier in mass balance assessments in order to maintain consistency over the whole time series of observations. Hence, "Hintereisferner" in this paper refers to all three glacier bodies.

The area of Hintereisferner in 2011 was 6.78 km², about 15% smaller than in 2001, when the first ALS campaign was conducted. The glacier front retreated by 390 m during the same period. The glacier elevation ranges from 2456 to 3720 m a.s.l. and the median altitude is 3039 m a.s.l. The accumulation area covers aspects from northeast to southeast while the long and narrow tongue faces northeast. Meltwaters feed the Hintereisbach, which joins the runoff from Kesselwandferner, Hochjochferner and a few smaller glaciers and subsequently drains into Rofenache and finally into the Ötztaler Ache, one of the major tributaries of the Inn River.

Hintereisferner is located in the 'inner dry Alpine zone' (Frei and Schär, 1998), which is amongst the driest regions of the entire European Alps. Precipitation in Vent (~1900 m a.s.l.), about 8 km west of the glacier terminus, reaches 677 mm a^{-1}, with air temperatures of 1.5°C in average (1906–2011). Precipitation amounts double at the totalizing rain gauge near the Hintereis research station (3026 m a.s.l.; Figure 1), reflecting the altitudinal difference of approximately 1100 m but also the enhanced precipitation activity further up the valley. Over the study period 2001 to 2011, the values for annual temperature and precipitation in Vent are 2.3°C and 676 mm, respectively. The mean annual 0°C-isotherm is located at ~ 2450 m a.s.l.

Like many glaciers in the Eastern European Alps, Hintereisferner has experienced strong shrinkage compared to its Little Ice Age maximum extent, which was reached sometime between 1847 and 1855 (Richter, 1888). Since that time, the glacier area in the Ötztal-Alps has shrunk by more than 50% (Fischer et al. 2015). After a period of rather stationary glacier lengths in the late 1970s and early 1980s (e.g. Patzelt, 1985), glacier mass loss and area shrinkage dominate with particularly high rates during and after the extraordinarily hot summer of 2003 (e.g. Abermann et al., 2009).

3 Mass balance methods and data

In this section we introduce the glaciological and the geodetic measurement methods used to obtain the annual mass balances of Hintereisferner. We first determine a common base for the two datasets, by the homogenization of glacier outlines and DTMs, followed by quantifying method-inherent uncertainties.

3.1 The glaciological method

Glaciological measurements of annual mass balance at Hintereisferner have been started in 1952 (Hoinkes, 1970) and are carried out regularly since then, resulting in one of the longest continuous glacier mass balance time series worldwide. The distribution of 40 to 50 (maximum 100) ablation stakes over the main tongue of Hintereisferner is a compromise between representative coverage and logistic feasibility (Kuhn et al, 1998; Fischer, 2009). During the study period no ablation stakes are placed in the upper part of the glacier, where the accumulation is usually determined by means of snow pits and probings at the end of the mass balance year. The location of individual snow pits has been more or less constant over the whole study period. Their number changed according to the varying extent of the accumulation area from none in e.g. 2002/03 up to 14 pits in 2003/04 (see Figure 1). The series follows the fixed date system as defined by the hydrological year, spanning from October 1st to September 30th of the following year, with additional measurements in spring and during about fortnightly visits between June and October.

The annual mass balance at each measurement point is derived by converting the individual change of surface height as obtained from stakes and pits. Ice ablation obtained from repeat stake readings is converted into point specific mass balance by applying an assumed constant density of 900 kg m-3. Accumulation is determined by measuring the snow depth in conjunction with depth-averaged snow density in snow pits. The point values and additional observational information such as the position of the snowline from an automatic camera and from terrestrial and air photographs, topographic conditions, and the expert knowledge about typical spatial patterns are the basis for drawing contour lines of equal mass balance values. The resulting areas of equal mean mass balance are then intersected with 50 m altitude bands in order to derive the vertical mass balance profile. By integrating over the altitude bands, both the total mass balance B_{glac} and the mean specific mass balance of the entire glacier b_{glac} are obtained (e.g. Kaser et al., 2003; Cogley et al., 2011). Results are submitted to the World Glacier Monitoring Service (WGMS) annually. In order to provide a common base for both the glaciological and geodetic analyses we re-generate the annual glacier outlines from the ALS data rigorously following the guidelines presented in Abermann et al. (2010). This led to minor changes (ε_{area}) in annual glaciological balances in the order of –0.015 to +0.039 m w.e. a^{-1}, accumulating to +0.12 m w.e. over the 2001 to 2011 period.

Before approaching the reanalysis of the annual surface mass balances of Hintereisferner for the time period 2001 to 2011 further uncertainties in the glaciological mass balances series must be addressed. The glaciological method suffers from uncertainties related to (i) point measurements and (ii) their spatial extrapolation over the entire glacier. For both uncertainty sources and due to the lack of respective data on Hintereisferner we synthesize appropriate information from the literature as follows.

Zemp et al. (2013) analysed, among others, the mass balance series of Hintereisferner for six periods between 1953 and 2006 and attributed an uncertainty of ±0.10 m w.e. a^{-1} to field measurements for the years after 1964 and doubled the value for the years before. For the spatial interpolation of point data they assigned values between ±0.14 and ±0.54 m w.e. a^{-1} with an average of ±0.33 m w.e. a^{-1} for the entire period. Further explanations are not provided by Zemp et al. (2013).

Fountain and Vecchia (1999) found combined uncertainties for (i) and (ii) of up to ±0.33 m w.e. a^{-1} by analysing the modelled variability of the mass balance of South Cascade glacier. Thibert et al. (2008) and Thibert and Vincent (2009) analysed 51 years of mass balance for Glacier de Sarennes and reported a combined annual uncertainty of ±0.20 m w.e. a^{-1} for (i) and (ii). For Gries- and Silvrettagletscher, Huss et al. (2009) assumed overall uncertainties related to (i) and (ii) of ±0.16 to ±0.28 m w.e. a^{-1}. By investigating the glaciological and geodetic mass balances of Storglaciären, Zemp et al. (2010) determined the random uncertainty for (i) and (ii) with ±0.10 m w.e. a^{-1} each, which resembles the results of Jansson (1999). For Findelengletscher, Sold et al. (2016) roughly estimated a random uncertainty of ±0.04 m w.e. a^{-1} for (i), referring to Huss et al. (2009), and of ±0.17 m w.e. a^{-1} for (ii) by evaluating contour lines drawn by 18 independent analysers. On Nigardsbreen, Andreassen et al. (2016) obtained a total point measurement uncertainty of ±0.25 m w.e. a^{-1} as the root sum square (RSS) of a false determination of the previous year's summer surface (±0.15 m w.e. a^{-1}), upwelling of stakes (±0.20 m w.e. a^{-1}), and wrong density assumptions of snow and firn (±0.05 m w.e. a^{-1}). Uncertainty of spatial integration was taken as ±0.21 m w.e. a^{-1}, made up by point measurements insufficiently covering both the vertical range and the total area of the glacier.

Based on the findings of Zemp et al. (2013) combined with expert knowledge about the study site, we assess the uncertainty related to point measurements at Hintereisferner, being in the order of σ_{point} = ±0.10 m w.e. a^{-1}, resulting in a decadal value of about ±0.32 m w.e. For extrapolating point data into reasonable patterns of mass balance, the contour line method uses expert knowledge. Based on Sold et al. (2016), we estimate a respective uncertainty of ±0.15 m w.e. a^{-1} for Hintereisferner. In addition and according to Andreassen et al. (2016), we assume that the extrapolation over areas not covered by point measurements inherits uncertainties of ±0.10 m w.e. a^{-1}. Hence, uncertainty due to spatial integration of the respective measurements over the entire glacier is defined to be $\sigma_{spatial}$ = ±0.18 m w.e. a^{-1} and result in decadal uncertainty of ±0.57 m w.e.

Overall uncertainties for the glaciological mass balances are calculated, according to the law of error propagation, leading to σ_{glac} = ±0.21 m w.e. for annual and ±0.65 m w.e. for the cumulated values.

3.2 The geodetic method

Between 2001 and 2011, eleven ALS flight campaigns had been carried out near the end of each mass balance year (see Table 1). During each ALS data acquisition campaign, the glacier was covered with a number of overlapping flight strips in order to increase the point density and to ensure high quality and complete coverage of the glacier (Wever and Lindenberger 1999; Geist and Stötter, 2007).

As there is essentially no high vegetation in the study area, ALS points are classified into ground points and flying objects (outliers) only. The ground points of all datasets are imported into a laser database system (Rieg et al., 2014) which facilitates storage and further processing. 1 m resolution DTMs are calculated for all datasets, whereby the mean value of all ALS points located in each cell represents the elevation of the cell. The elevation values for the few raster cells that do not contain a single point are interpolated from the neighbouring cells using a least squares method.

In order to provide high-quality DTMs used for mass balance calculations, horizontal misalignment of the DTMs being differenced has to be excluded. Therefore a statistical co-registration correction procedure as suggested by Nuth and Kääb (2011) was performed for this study. Following Joerg et al. (2012) we applied the first two steps of the procedure to the ice-free areas for identifying potential horizontal shifts and vertical offsets between two ALS-DTMs. The statistical co-registration reveals horizontal shifts smaller than the DTM pixel resolution with no elevation-dependent bias, and the DTMs can be subtracted from each other without performing DTM corrections.

The total volume change ΔV between two dates is then derived from the respective elevation difference Δh_k of the two grids at pixel k with cell size r of the DTMs, summed over the number of pixels k covering the glacier at the maximum extent and is expressed as (cf. Zemp et al., 2013):

$$\Delta V = r^2 \sum_{k=1}^{K} \Delta h_k \ , \qquad (1)$$

For a comparison with the glaciological balance, ΔV is then converted into a specific mass balance in the unit metre water equivalent (m w.e.):

$$B_{geod} = \frac{\Delta V}{S_{t1}} \times \frac{\bar{\rho}}{\rho_{water}}, \qquad (2)$$

where $\frac{\bar{\rho}}{\rho_{\text{water}}}$ is the ratio between the average bulk density of ΔV and the density of water, t_1 referring to the first acquisition date.

Despite a thorough co-registration, surface elevation differencing of two DTMs is still subject to various uncertainties. The vertical accuracy of the raw ALS point data was first assessed by comparing the point clouds with differential global navigation satellite system (dGNSS) measured points on a homogeneous horizontal surface outside the study area (e.g. in our case a football field in Zwieselstein 20 km down-valley of Hintereisferner). Table 1 shows the standard deviations (SD) of vertical accuracies of the individual datasets.

As the reference surface does not reflect the surface conditions in terms of slope, aspect and roughness, and therefore is not representative for vertical accuracies, Bollmann et al. (2011) compared dGNSS ground control points with laser returns (deviation to laser points 0.07 m, standard deviation 0.08 m) and calculated an absolute slope-dependent vertical accuracy for Hintereisferner ALS point data (<0.10 m on slopes <40°). Sailer et al. (2014) analysed the uncertainties resulting from rasterizing laser point clouds, revealing that a cell size of 1x1 m as used for our study causes only negligible errors of less than 0.10 m.

For the raw geodetic balance (b_{geod_raw}), the results of DTM differencing over stable terrain are taken to define uncertainties associated with the DTM comparison. Therefore, we selected five stable control areas (~3 x 10^4 m²) surrounding the glacier (Figure 1), in order to quantify grid-based uncertainties of spatially averaged elevation differences. As the standard deviation of the elevation differences (SDΔz, Table 2) provides information on the spatial variability of the selected stable areas, we used the related RSS for an approximation to our DTM uncertainty:

$$\sigma_{DTM} = \sqrt{\sum_1^i SD_\mathrm{i}^2}, \tag{3}$$

where SD is the standard deviation within the reference surfaces i. The result was converted into mass using the density of ice. Comparison of the differential DTMs (dDTMs) show uncertainties of $\pm 0.06 < \sigma_{DTM} < \pm 0.17$ m w.e., resulting in ±0.36 m w.e. cumulated over the observation period (01-11cum; Table 3). In contrast, the 2001 to 2011 one step application of the geodetic method (01/11; Table 3) yields a value of $\sigma_{DTM} = \pm 0.14$ m w.e.

Table 3 summarizes the results of sections 3.1 and 3.2 and shows the differences between the adjusted glaciological and the raw geodetic mass balances ($b_{glac.hom} - b_{geod.raw}$).

4 Accounting for method inherent differences

Figure 2 shows the glaciological and the geodetic mass balance series as revised in sections 3.1 and 3.2. The expected differences vary from year to year, being particularly high in some years (Table 3). The potential causes of these discrepancies in the mass balance series are related to snow cover at the time of ALS acquisition (4.1), different glacier-wide density assumptions in mass balance calculation (4.2), survey date differences between the glaciological and geodetic observations (4.3), the way the methods consider the existence of crevasses (4.4), and the differences between the surface (glaciological) and the total (geodetic) mass balance (4.5).

4.1 Differences induced by snow cover present in DTMs

Whereas the vertical accuracy tends to be very high, biases as a result of snowfall events preceding the ALS surveys influence the calculated volume change significantly. From the analysis of elevation differences in the non-glaciated terrain, the mean difference between two DTMs ($\overline{\Delta z}$ stable areas; Table 2) with

$$\varepsilon_{DTM} = \frac{\sum_1^n \overline{\Delta z_i}}{n}, \tag{4}$$

where n is the number of DTM grid cells covering non-glacierized terrain, can be used for inevitable volume corrections, caused by preceding snow fall events.

For the periods 2001/02, 2005/06, 2006/07 and 2007/08 the investigation of stable areas within the dDTMs revealed snow induced vertical offsets between |0.18| and |0.58| m ($\overline{\Delta z}$; bold numbers in Table 3). In all other dDTMs, the vertical bias was below 0.10 m. In 2004 and 2010 a snow fall event occurred some days before the ALS measurements. However, this is not reflected in the stable areas of the respective dDTM, because the snow in non glacierized areas had melted from off-glacier surface by the time of the ALS survey. This leads to a very low offset in the non-glacierized terrain in the related mass balance periods. Yet, as snow cover increases, the ALS elevations measured on reference surfaces have to be cross-checked with the closest field survey data for snow depth estimation and subsequently corrected. Based on the altitude distribution of stable areas and in-situ measurements a linear regression in 50 m elevation bands yielded mean snow depths of 0.52 m in 2001, 0.23 m in 2004, 0.46 m in 2005, 0.13 m in 2006, 0.12 m in 2007 and 0.26 m in 2010. This leads to adjusted DTMs and, finally, to a respective mass balance correction value ε_{DTM} (Table 5). Furthermore this approach was integrated to the estimation of differences related to unequal survey dates (see section 4.3)..

4.2 Density conversion

One of the method-inherent differences between glaciological and geodetic method can be found in the density conversion. Glaciological mass balances are derived from mass change measurements based on well constrained in situ density measurements, whereas the geodetic ones are based on volume change measurements, which require conversion to mass by an estimated density for the material lost or gained (e.g. Thomson et al., 2016). Several studies assume that density in the accumulation area is constant over time and, hence, use glacier ice density for the conversion (e.g. Andreassen, 1999; Haug et al., 2009). As long as snow or firn is present, the density of ice (ρ_{ice}=900 kg m^{-3}) causes an overestimation of the mass change. Hence, only below the equilibrium line altitude (ELA), where altitudinal changes are either due to ice ablation or emergence, the density of ice is appropriate. However, if firn line changes are known, the volume to mass conversion can be approximated by an average density of firn (e.g. Sapiano et al., 1998; Prinz et al., 2011). To make a first calculation of mass change (Figure 2), we follow the recommended approximation for density conversion of 850 ±60 kg m^{-3} suggested by Huss

(2013). However, this approach revealed differences in some periods of the data series, as the assumption of Huss (2013) is suitable for geodetic analyses over periods which span over five years or more and which show relatively stable mass balance gradients, non-negligible changes in volume and a relatively stable extent of the firn region.

Therefore we designed a pixel-based surface classification workflow, in order to account for changing firn areas. The present classification is based on ALS-intensity data as described by Höfle and Pfeifer (2007). Following Fritzmann et al. (2011), a classification of ice and firn zones on the glacier surface for each survey year could be achieved (Figure 3).

If no suitable intensity data are available from the ALS, the most contemporary ortho-images (e.g. for the year 2010) and/or LandsatTM images (e.g. for the years 2001 and 2004) are used for surface classification. To incorporate the changing extent of the perennial firn zones we subtracted the surface grids of the respective mass balance periods from each other and reclassified the resulting new surface raster. The glacier surface is classified in two categories: glacier ice with a density of 900 ±17 kg m^{-3} and perennial firn with 700 ±50 kg m^{-3} (Ambach and Eisner, 1966; Huss, 2013), whereas the difference to maximum/minimum estimates (±17 and ±50 kg m^{-3}) serve as an uncertainty measure within our approach (σ_κ; Table 5). The resulting grids are used to convert volumetric changes into a mass for every pixel (see equation 2). For a better interpretation we introduce a dimensionless conversion factor as

$$\kappa = \frac{\rho_{ice} * \Delta V_{ice} + \rho_{firn} * \Delta V_{firn}}{\rho_{water} * \Delta V_{total}}\,. \tag{5}$$

Corresponding volume-to-mass conversion factors (κ) lie in the range of 820 and 930. The change in mass balance values compared to the raw geodetic results (Table 2) is ascribed to the density conversion deviation (ε_κ; Table 5).

4.3 Survey date differences

Temporal differences between the geodetic and glaciological observations need to be addressed. To align the geodetic dates with the stratigraphic year used for the glaciological mass balance measurements, a multi-methodical approach was applied, incorporating field measurement minutes, DTM analysis results from section 4.1 and data from in situ measurements.

Apart from 2011 with in situ measurements conducted on the same day as the ALS flight (Table 4), the changes in snow depth and ice ablation between the two measuring dates have to be considered. If the date of the ALS acquisition deviates from the 30th of September (end of the hydrological year), the geodetic mass balance is adjusted to the fixed dates by linear extrapolations as follows. In case of ablation between the survey and the fixed date the extrapolation is based on the ablation trend over the immediately preceding time for each stake. This is calculated from available stake readings during the summer justified by extrapolated air temperature data from Vent allowing ablation conditions. In the case of accumulation between the survey and the fixed date, the precipitation gradient between Vent and five rain gauges in the Hintereisferner basin (Figure 1) is used for adjustment to the fixed date. The snow-rain threshold of 0°C is obtained from the Vent temperatures along a lapse rate of 0.0065°K m^{-1}.

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The survey date adjustment is performed individually for each annual geodetic mass balance, dependent on the presence/absence of snow during the field survey and ALS data acquisition as well as on the difference between the survey dates and the end of the hydrological mass balance year. Accordingly, we proceeded as follows:

i) If there was no snow cover during both surveys, and the ALS campaign took place before the field survey, an elevation dependent mean ablation gradient as described above is applied. This is the case in 2003 and 2008.

ii) If there was no snow cover present during the field survey, but before a later ALS campaign, the mass balance has been adjusted to the survey date by subtracting the amount of snow from the corresponding DTM, as described in section 4.1. This is the case for the years 2006 and 2007. The amount of snow determined agrees well for these years with extrapolated precipitation data using the altitudinal gradients between 5 rain gauges in the area.

iii) If snow was present during the field survey, but the ALS campaign had been conducted before the snowfall event, the mass of the snow cover measured during the field survey is added to the geodetic mass balance using the measured densities and the linear regression of snow probings for the elevation distribution. This is the case in 2002 and 2008.

iv) If snow was present during the field survey and the ALS data acquisition, the ALS-DTM was adjusted regarding the snow cover conditions. When the ALS campaign was conducted after the field survey, the geodetic determined snow height is subtracted (section 4.1), and the mass of snow determined by field survey is added to the geodetic mass balance. This is the case for the years 2001, 2004, 2005, 2010.

There were no cases with snowfall between both surveys when the ALS data have been acquired before the field data. It is noted that two corrections have been applied for the year 2008 when the ALS data acquisition took place 21 days before the field survey and ablation as well as accumulation occurred. No survey date correction was necessary for 2009 and 2011.

4.4 Representation of crevasses

While crevasses are neglected in the glaciological method, they are partially resolved in the geodetic method. Although some crevasses might have been covered by snow during data acquisition, in all DTMs a number of big crevasses are visible, which open during the ablation season. However, depending on snow / melt conditions, crevasses are differently represented in the respective dDTMs, due to the ice movement between two ALS acquisitions and therefore have different impacts on mass balance calculations. We detected crevasses by assuming that they are deviations from a regular homogenous surface. By using the variance as a measure of terrain smoothness and applying a closing filter, we derived a surface without crevasses (for detail we refer to Kodde et al., 2007 and Geist and Stötter, 2010). Hence, we calculated the volume change of a "crevasse free" glacier, to quantify differences due to open crevasses in the geodetic mass balance (ε_{crev}; Table 5).

4.5 Internal and basal mass changes

Internal and basal mass balances are not captured by the glaciological method, but are implicitly included in the geodetic mass balances. Thus, when comparing glaciological with geodetic balances, internal and basal mass changes need to be assessed separately. Particularly for mountain glaciers studies on this topic are rare and published values represent estimates rather than verified measurements.

On Storglaciären, for example, Östling and Hooke (1986) estimated the contribution of basal melt due to geothermal heat as about 0.001 m w.e. a^{-1} and Holmlund (1987) suggested 0.01 m w.e. a^{-1} of internal melting by released potential energy from descending water. Albrecht et al. (2000) considered internal ablation due to ice motion being small on Storglaciären and, thus, negligible. For South Cascade Glacier, Mayo (1992) estimated the combined effect of either frictional or geothermal basal melt, melt by the loss of potential energy of water flowing through the glacier and melt by the loss of potential energy of the ice mass as 0.09 m w.e. a^{-1}. Thibert et al. (2008) estimated 0.48 m w.e. of basal ablation due to geothermal heat and 0.42 m w.e. of internal due to water flow on Glacier de Sarennes over a period of 51 years. Huss et al. (2009) estimated the contribution to ablation from geothermal heat, internal deformation, and basal friction as –0.01 m w.e. a^{-1} for glaciers in the Alps. Andreassen et al. (2016) calculated internal and basal ablation due to heat of dissipation based on Oerlemans (2013) for 10 glaciers in Norway, yielding a range of 0.01 to 0.08 m w.e. a^{-1}. Sold et al. (2016) assessed a value of 0.014 m w.e. a^{-1} for internal and basal processes at Findelengletscher following different previous studies (e.g. Herron and Langway, 1980; Pfeffer et al., 1991; Medici and Rybach, 1995; Huss, 2013).

In this study, we assess internal and basal ablation due heat of dissipation following Oerlemans (2013) and Andreassen et al. (2016), because it is the most appropriate method for the available data for Hintereisferner. The methodical disregard of internal and basal processes in the glaciological mass balance (ε_{int}; Table 5) is assumed to yield values of internal ablation around −0.04 m w.e. a^{-1}, which corresponds well to published data in Oerlemans (2013) for glaciers of the size and climate setting like Hintereisferner. According to Huss et al. (2009) melt from basal friction and geothermal heat flux was estimated about −0.01 m w.e. a^{-1} (hence, −0.05 m w.e. a^{-1} cumulated). As the uncertainty of internal and basal processes was not subject to any detailed analyses due to lack of independent data, we assume a value of our estimation of ±30% or ±0.015 m w.e. a^{-1} (σ_{int}; Table 5).

5 Reanalysing the glaciological records

The geodetic balance over the entire study period was mainly affected by snow being present in the year 2001 resulting in ε_{DTM} = +0.29 m w.e. Taking snow heights and densities in DTMs of individual years into account leads to $-0.41 < \varepsilon_{DTM} < +0.32$ m w.e. (section 4.1). The value of –0.41 m w.e. occurs in 2004/05 when snow was present at both ALS flight campaigns (Table 5) making up for 37% of the initial mass balance value. Applying the workflow for the spatially distributed density conversion (section 4.2) leads to $-0.04 < \varepsilon_{\kappa} < +0.31$ m w.e., with maxima in 2002/03 and 2005/06 (Table 5). These maxima are due to the total lack of snow and firn at the end of these mass balance years. The uncertainty

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related to our density assumption (section 4.2) is between $\pm 0.01 < \sigma_\kappa < \pm 0.18$ m w.e. with ±0.22 m w.e. over the entire period of record. As dates of the ALS campaigns diverge from the end of the hydrological year a survey date correction is required. Values for related adjustments are in the order of $-0.08 < \varepsilon_{survey} < +0.06$ m w.e. (section 4.3 and Table 5). Significant melt amounts between ALS flight and field survey dates occur on small parts of the glacier tongue only. E.g. a nearly 1 m ice ablation at the lowest stakes of Hintereisferner measured between 30th September (field survey) and 8th October (ALS campaign) 2006 corresponds to a glacier wide specific mass loss of only 0.03 m w.e. during the same time.

The differences related to the consideration of crevasses (ε_{crev}) in the geodetic method are insignificantly small and vary between −0.04 and +0.06 m w.e. with +0.05 m w.e. for the 2001 to 2011 period (section 4.4 and Table 5). While the glacier wide effect of internal mass changes is small on an annual basis (ε_{int} = +0.05 m w.e. a^{-1}), it is significant on the decadal timescale (+0.50 m w.e.) (section 4.5 and Table 5).

Annual totals for method-inherent differences (ε_{geod}) are in the range of −0.40 to +0.57 m w.e. and accumulate to +0.28 m w.e. for the 2001 to 2011 period while the respective uncertainties are $\pm 0.07 < \sigma_{geod} < \pm 0.20$ m w.e. and ±0.51 m w.e. for the cumulated values. The 2001 to 2011 one step application of the geodetic method shows ε_{geod} = +0.77 m w.e. and σ_{geod} = ±0.20 m w.e. All applied corrections accounting for method inherent differences (ε) as well as numbers for related uncertainties (σ) are summarized in Table 5. Figure 4 shows the vertical profiles of the now corrected glaciological and geodetic mass balances for each year from 2001/02 to 2010/11.

The geodetic mass balance of Hintereisferner corrected for ε_{geod} for the ten years' period 2001 to 2011 is –12.99 ±0.51 m w.e. and –12.45 ±0.20 m w.e. for the 2001 to 2011 one step analysis (Table 6). In turn, the homogenized glaciological mass balance series (–12.04 ±0.65 m w.e.) is 0.95 m w.e. and 0.31 m w.e. less negative respectively. Figure 5 depicts the annual glaciological versus geodetic mass balances and their uncertainty ranges. All but three annual data pairs match satisfyingly within the assessed uncertainty ranges. The largest positive differences ($b_{glac} - b_{geod} = \Delta b$) between the two methods occur in the balance years 2002/03 with Δb = +0.92 m w.e. and 2005/06 with Δb = +0.60 m w.e. respectively. In 2006/07 the difference between glaciological and geodetic method is –0.45 m w.e., which means the geodetic result is less negative than the glaciological one. Note that the three years displaying the largest differences are at the same time the years with the most negative annual balances.

Following Zemp et al. (2013) we perform a statistical significance test with

$$\delta = \frac{\Delta b}{\sqrt{\sigma_{glac}^2 + \sigma_{geod}^2}}, \qquad (7)$$

where the term $\sqrt{\sigma_{glac}^2 + \sigma_{geod}^2}$ represents the common variance (σ_{comvar}) defined as the RSS of the method-inherent uncertainties (Table 6). The more consistent the two methods, the closer δ is to zero and the null-hypothesis (H_0) on the 95% confidence level to be accepted.

As δ falls within the 95% confidence interval (|δ| < 1.96) for seven annual and the cumulative mass balance values, the two applied methods can be considered as statistically coherent. Hence, for these years, the glaciological method accurately captures the annual mass changes at Hintereisferner. From the common variance it is also possible to calculate the smallest bias that could theoretically be detected in the glaciological record. The bias calculated at the 5% risk limit lies between 0.79 and 1.03 m w.e. a^{-1} and far above the uncertainty of 0.21 m w.e. a^{-1} in the glaciological balance measurements. In contrast, the detectable bias decreases with the length of the analysed period, which can be explained by error propagation. However, it is not possible to statistically identify any biases that might explain the observed discrepancies in the mass balance years 2002/03, 2005/06 and 2006/07 (see Figure 5).

In search for possible causes of these discrepancies we explore the parameter space in which individual components of ε_{geod} vary. The influence of temporary snow cover (ε_{DTM}) on the geodetic mass balances is high and a thorough consideration ensures that the results are within the 95% confidence interval. In contrast, the survey date differences show little effect.

Concerning the conversion of glacier volume to mass changes, we used a new classification approach and a dimensionless conversion factor (κ). Calculated values for κ correspond to densities in the range of 820–930 kg m^{-3}. This is in line with a generally recommended glacier-wide value of 850±60 kg m^{-3} (Huss, 2013). Nevertheless, in 2010 κ reaches 930, a value which at a first glance appears unrealistic. In this year opposite signs of elevation changes in the accumulation and ablation area compensate for each other, which results in a conversion factor which is higher than the density of ice. Such is possible in cases of (i) short observation periods (1–3 years), (ii) small volume changes, (iii) strong year to year changes in the vertical mass balance gradients, or combinations of these factors. Our approach accounts for year to year changes in the spatial extent and distribution of the snow/firn zones. Highest uncertainties arise in years 2002/03 and 2005/06 when all snow from the previous winter melted entirely. As the uncertainty associated with density is of particular importance (Moholdt et al., 2010; Huss, 2013) we conducted a sensitivity test for the periods of good agreement by holding all other parameters fixed. Densities calculated within our κ-range (Table 5) still lead to results within the 95% confidence interval.

As crevasses may influence geodetically calculated volume changes we assessed their impact on the geodetic method. The largest impact (0.06 m w.e., or 3% of glaciological mass balance) was detected for 2002/03 when numerous crevasses opened due to the extremely hot summer causing extraordinary high glacier velocities (Geist and Stötter, 2007). Hence, crevasses contribute negligibly to the differences between geodetic and glaciological mass balances.

Internal and basal fluxes are also of rather minor importance (–0.05 m w.e. a^{-1}; section 4.5) and do not change the differences between the two data series substantially. Yet, we note that in years with extreme melt rates as in 2003 and 2006 meltwater penetrates the glacier body during the ablation season and leads to the internal melt rates possibly exceeding the above estimate.. However even a doubling to –0.10 m w.e. a^{-1} does not explain the large discrepancies between the glaciological and geodetic method in the years 2002/03, 2005/06 and 2006/07.

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Other uncertainties possibly contributing to the high mass balance discrepancies in 2002/03, 2005/06 and 2006/07 may be method-inherent uncertainties related to the field measurements, such as the false determination of the last year's summer surface. This might be an issue for the high discrepancies in the individual survey years, but cannot be quantified due to the lack of corresponding information.

However, none of the discussed method-inherent uncertainties can explain the considerable high differences in the mass balance years 2002/03, 2005/06 and 2006/07. Nevertheless, a first hint for a potential reason is given by looking at the spatial mass balance distribution as shown in Figure 6 for the exemplary 2002/03.

In all three years glaciological point data from elevations above 3000 m a.s.l. are basically missing on Hintereisferner, but all three years of concern are among the most negative ones (Figure 7). After several years of gradual degradation of the firn body, ice had suddenly become exposed over all altitude bands by mid of August 2003 with consequent effects on albedo and the energy budget. From then on, the East and South facing high slopes of Hintereisferner had been exposed with a very low albedo to high solar radiation for 6 to 7 weeks of the exceptionally warm and dry summer 2003 (Fink et al., 2004). As a consequence, the mass loss in the former accumulation area of Hintereisferner became large and almost constant above 2800 m a.s.l. (> 50% of the glacier area). This effect had been observed on a smaller glacier some years earlier (Kaser et al., 2001). By facing this sudden change of the mass balance regime in 2002/03 and the mass balance network not being adapted in time, ablation rates measured at the highest stakes on the flat tongue (at about 3000 m a.s.l.) had been multiplied with the observed ice exposure time of the higher slopes (G. Markl, personal communication). The thereby disregard of higher solar radiation intensity on the slopes compared to the flat tongue are considered to be a possible reason for the differences between the two methods.

While higher winter snow cover buried the dark ice surface far enough into the autumns of 2004 and 2005 the high glacier portions remained protected, even allowing obtaining snow pits at the end of summer.

In the hot July of 2006 dark ice became again exposed and the 2002/03 problem was repeated. In 2006/07 when the glaciological mass balance obtains more negative values than the geodetic one we face a different situation. In summer 2007 there was a number of snow falls leading to high surface albedo in the upper part of Hintereisferner while stake measurements in the lower part of the glacier indicated relatively high ablation rates. The lack of metadata for this particular year disables any further discussion and interpretation. In 2002/03, 2005/06 and 2006/07 we argue for the geodetic data being closer to reality than the glaciological ones as recommended by Thibert et al. (2008) and Huss et al. (2009). For all other years where differences between the methods are statistically insignificant and where error bars overlap we keep the glaciological data in the record. The crucial effect of replacing the three problematic years is well emphasized in the cumulative mass balance curves shown in Figure 8.

Additional confidence for our approach comes from comparing the 2002/03, 2005/06 and 2006/07 mass balances of Hintereisferner with that of Silvrettagletscher (2.7 km², Switzerland, 52 km away), Jamtalferner (3.7 km², Austria, 45 km), Weißbrunnferner (0.5 km², Italy, 35 km) and Vernagtferner (7.9 km², Austria, 6 km). While in the years 2002/03 and 2006/07 original Hintereisferner values lay outside the spread of the other glaciers' mass balances and the reanalysed ones are inside, the 2005/06 originals are inside and the reanalysed value becomes the most negative one in Figure 9. This is of no surprise with Hintereisferner being the lowest reaching glacier of all and among the most negative result in all analysed years. A more comprehensive discussion and justification for the different relative positions in Figure 9 would require a detailed investigation on local conditions including meteorological patterns for each individual glacier and mass balance year.

6 Conclusions

Over the past decades it has become a standard procedure to review the annual glaciological data alongside with decadal geodetic mass balances from a variety of sources (e.g., Kuhn et al. 1999; Hagg et al., 2004; Cox and March, 2004; Thibert et al., 2008; Huss et al., 2009; Fischer, 2011; Galos et al. 2017). None of the mentioned studies uses annually obtained geodetic data series. Geist and Stötter (2007) were the first and so far only authors comparing glaciological and geodetic results on an annual timescale for 2001 to 2005. Their findings reveal considerable differences, especially in the year 2002/03. Yet, the study focuses on methodical issues only and does not aim at re-analysing the glaciologically obtained mass balances. It does neither include a thorough data homogenisation nor a robust uncertainty discussion.

In our review of the 2001 to 2011 Hintereisferner mass-balance record we showed that the consideration of method-inherent differences, such as snow cover, survey dates and density assumptions, is mandatory for accurately calculating annual geodetic mass balances. In turn, crevasses and internal processes seem not to play a key role. The largest potential source for differences between the geodetic and glaciological method on the annual scale is the presence of a snow cover. Our method allows us to correct for method-inherent differences for every pixel and provides an appropriate basis for detecting discrepancies in the direct glaciological method. However, our reanalysis approach requires a variety of meta-information and raw data, which can limit its applicability to other sites or cases. However, the corrected geodetic data series show that the glaciological method successfully captures the mass change in seven out of ten mass balance years and both methods generally agree on the annual as well as decadal time scale.

Our analysis shows that in years with very negative mass balances and a low extent of the accumulation area, the glaciological measurement network has to be adapted accordingly. In the case of Hintereisferner, this means that additional ablation stakes in higher parts of the glacier are needed to properly assess the mass changes in regions where snow measurements could be performed in former times. Missing these changes, a resulting lack of respective data is often tried to overcome with different mass balance extrapolation approaches. In the 2001 to 2011 Hintereisferner series the application of such approaches led to considerable deviations from the geodetic results in three years and the careful revision of both series gives support for favouring the geodetic data. Hence, we conclude that in times of increasing availability of high resolution topographic data, geodetic mass balances can represent a valuable possibility to overcome shortcomings in the glaciological measurements even on an annual scale if these data are thoroughly analysed.

Although major discrepancies between the glaciological and geodetic methods on Hintereisferner could be explained by our workflow, further glaciological investigations should address a better quantification of error sources, such as internal and basal processes, in both the glaciological as well as geodetic mass balances. Moreover, in times of vanishing firn areas and disconnecting glacier tributaries, existing measurement networks might have to be reassessed.

With the high-quality DTMs (e.g. ALS derived DTMs) reliably reproducing the annual mass balance the here presented workflow is recommended for i) a re-analysis of annual glaciological with annual geodetic data and ii) as a grid based tool for a glacier-wide geodetic mass balance of high spatial resolution suitable for a better understanding of the nature of the differences in the two methods.

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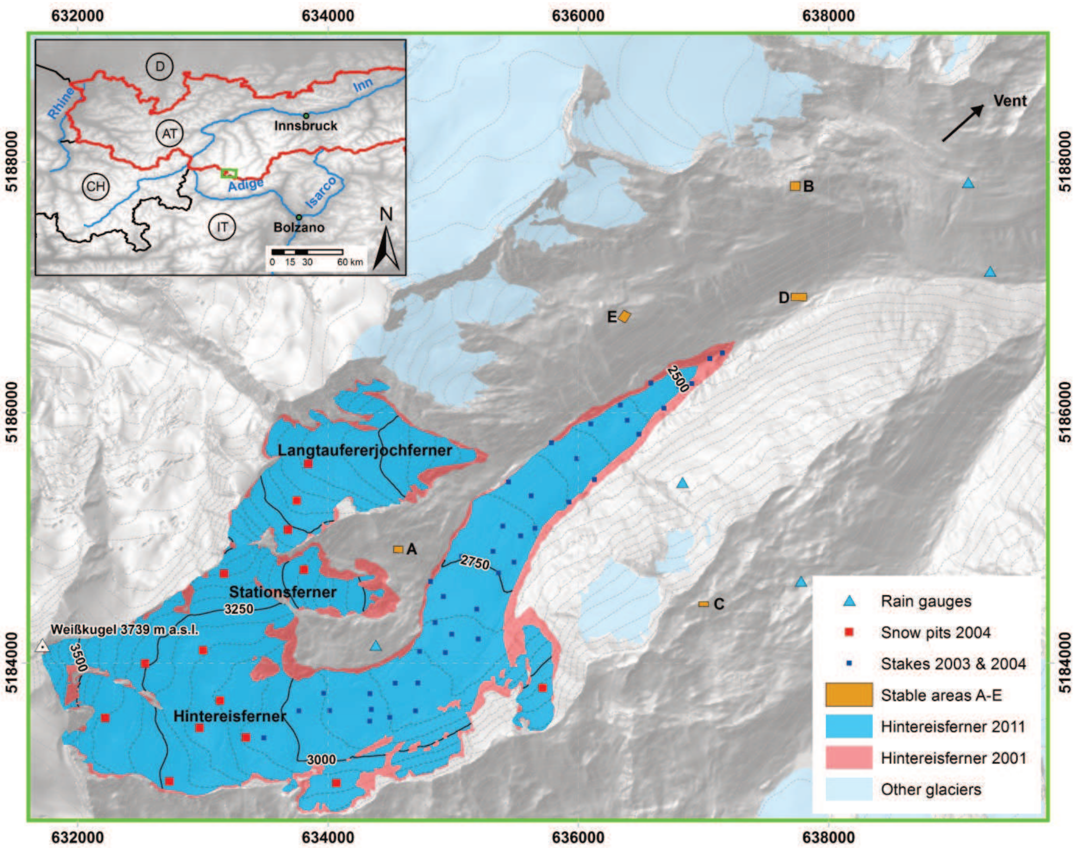

675 Figure 1: A map of Hintereisferner with the locations of the rain gauges and the glaciological mass balance measurement points in 2004 as an example. Also depicted are the glacier outlines for 2001 and 2011. Note that in 2003 no accumulation measurements have been carried out, thus, only the ablation stakes were available. Coordinates are in WGS84/UTM32N.

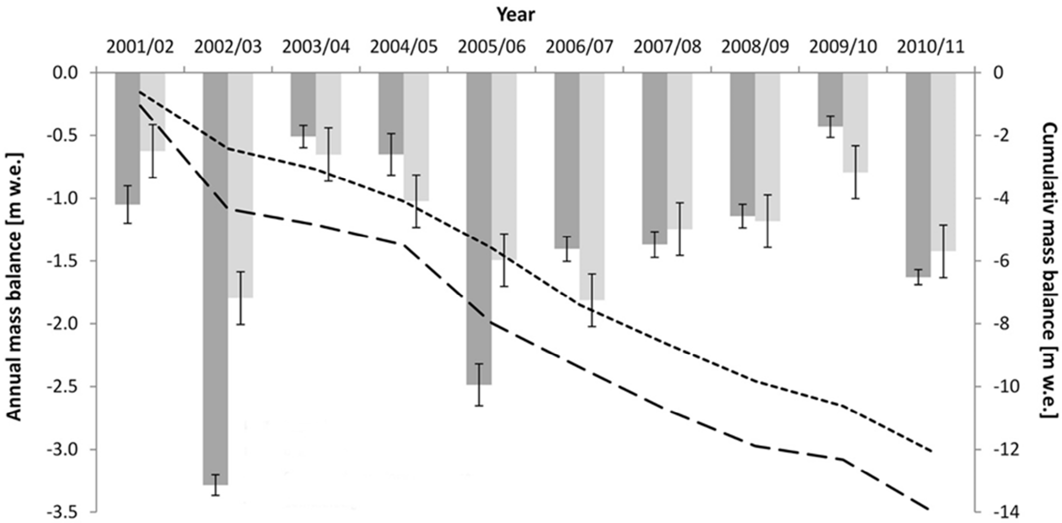

Figure 2: First order comparison of the annual and cumulative area adjusted glaciological (bglac_hom; light grey bar and dotted black line) and raw geodetic mass balances (bgeod_raw; dark grey bar and dashed black line) of Hintereisferner in the period from 2001 to 2011.
680 Method-inherent uncertainties (σDTM for geodetic, σpoint and σspatial for glaciological balances) are indicated by horizontal lines, respectively.

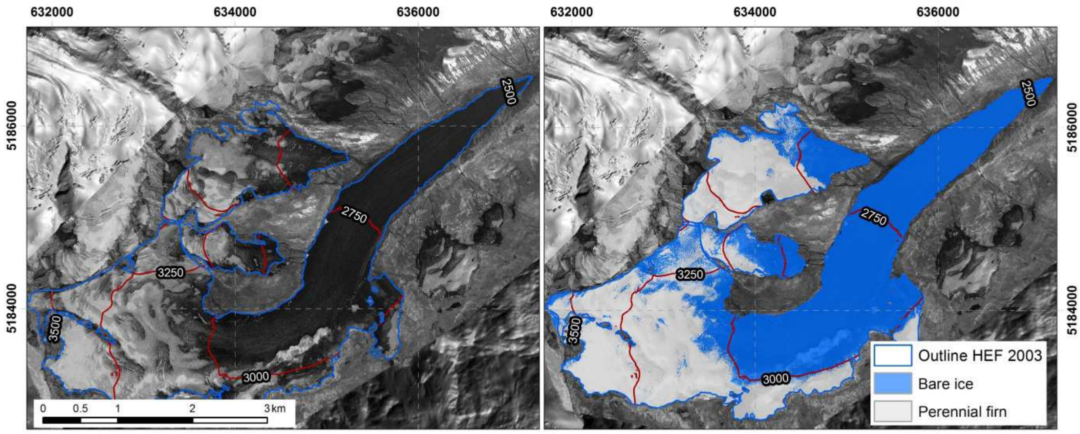

Figure 3: Intensity of the reflected laser beam of the ALS acquisition in 2008 (left) and derived surface classes (right). The classes are perennial firn with an average density of 700 ±50 kg m-3 and bare glacier ice of 900 ±17 kg m-3. Map coordinates are in WGS84/UTM32N.

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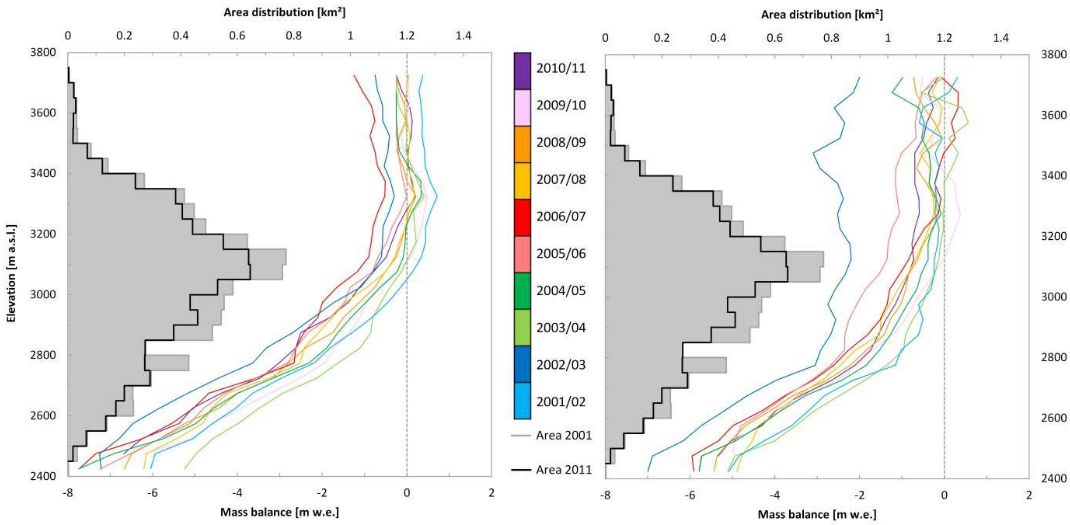

690 Figure 4: Corrected annual glaciological (left) and geodetic (right) vertical mass balance profiles for the period 2001/02–2010/11. Note that highest differences, which occur in the years 2002/03 (dark blue line) and 2005/06 (light red line) are also visible in the balance profiles at elevations above 2900 m a.s.l.

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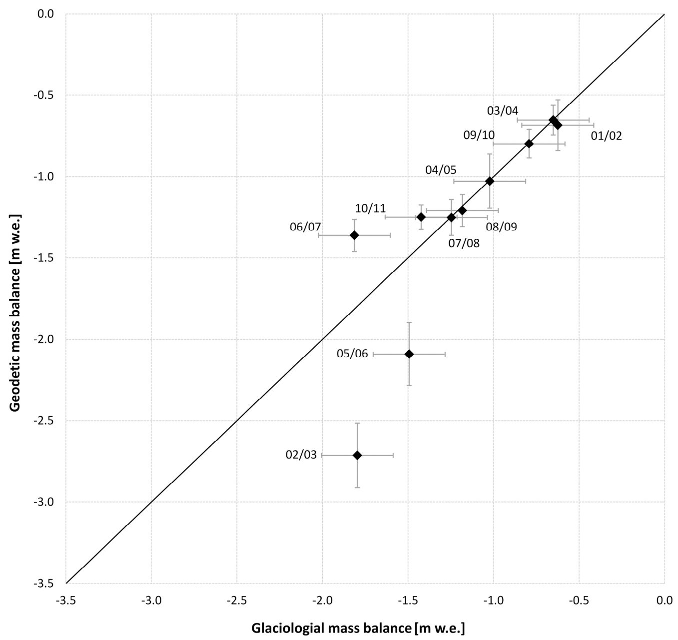

695 Figure 5: Annual glaciological vs. geodetic mass balance. Both series are corrected for method-inherent differences and plotted with uncertainties (grey crosses). The black diagonal line marks equal balances from both methods.

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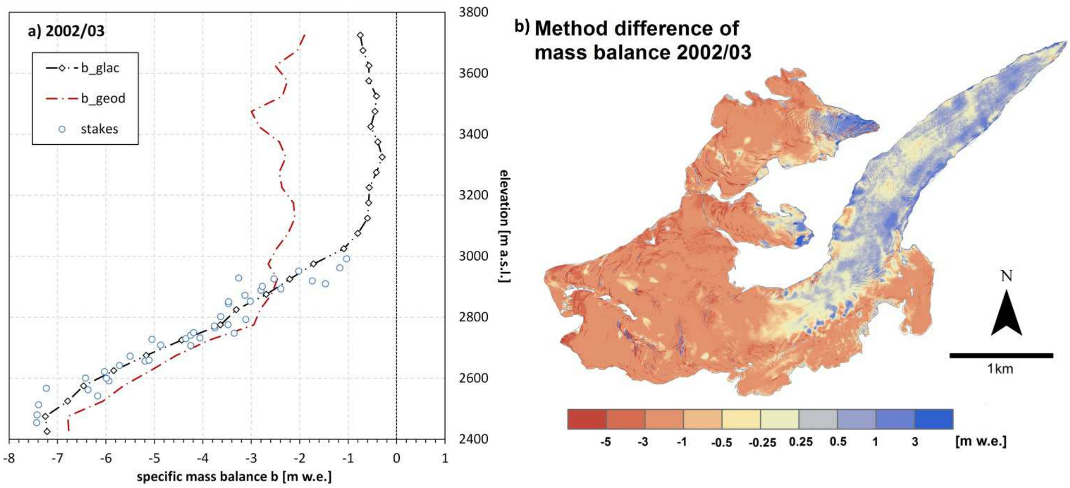

Figure 6: The extraordinary mass balance year 2002/03. (a) Comparison of vertical mass (b_{glac}; b_{geod}) and the distribution of accumulation and ablation measurements. (b) Spatial distributed difference of the methodical results with main deviations between the methods above 3000 m a.s.l.where in situ observations are missing.

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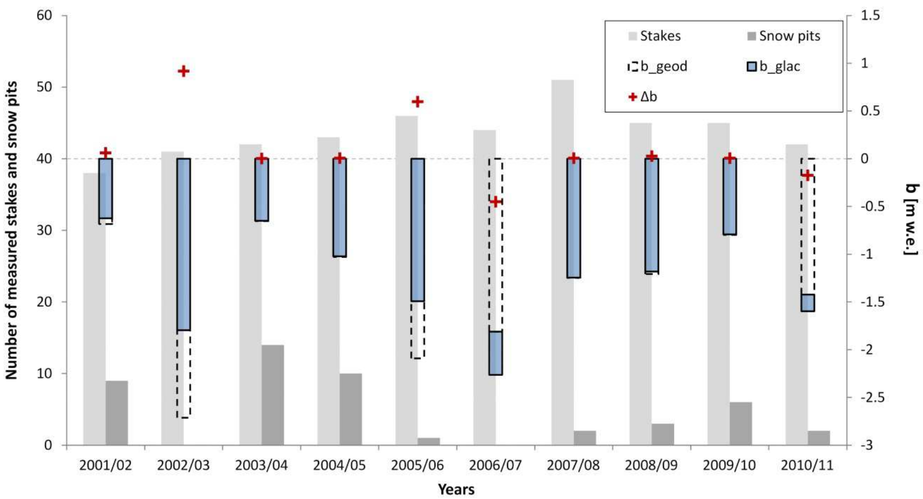

705 Figure 7: Comparison of mass balances (b_{glac}; b_{geod}) and their differences (Δb) with number of accumulation and ablation measurements.

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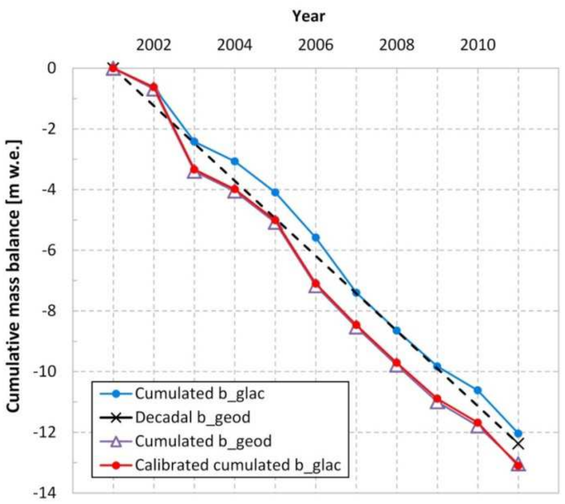

Figure 8: Calibration of glaciological mass balance series for the period 2001–2011 with the geodetic surveys for Hintereisferner. Cumulative adjusted mass balance (b_{glac}) is calibrated with the geodetic mass change (b_{geod}) for the respective years 2002/03, 2005/06 and 2006/07 resulting in calibrated b_{glac}.

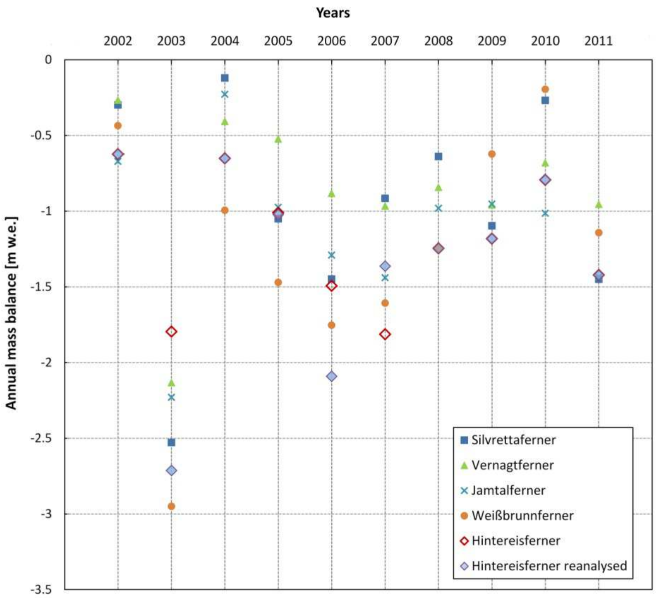

Figure 9: Comparison of original and reanalysed annual glaciological mass balances of Hintereisferner with different glaciers measured in the surrounding of Hintereisferner.

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715 Table 1: Key parameters for the 11 ALS data acquisition campaigns at Hintereisferner from 2001 to 2011. Point density is averaged over the study area, while the horizontal accuracy is calculated based on a flat reference area in vicinity of the study area.

Date of acquisition	Optech sensor	Mean height above ground [m]	Max. scanning angle [degrees]	Pulse repetition frequency (Hz)	Across track overlap (%)	Average point density (points/m²)	Vertical accuracy standard deviation (SD) (m)
11.10. 2001	ALTM 1225	900	20	25000	24	1.1	n.a.
18.09. 2002	ALTM 3033	900	20	33000	24	1	0.1
26.09. 2003	ALTM 1225	900	20	25000	24	1	0.06
05.10 .2004	ALTM 2050	1000	20	50000	24	2	0.07
12.10. 2005	ALTM 3100	1000	22	70000	50-75	3.4	0.07
08.10. 2006	ALTM 3100	1000	20	70000	37 - 75	2	0.08
11.10. 2007	ALTM 3100	1000	20	70000	37 - 75	3.4	0.06
09.09. 2008	ALTM 3100	1000	20	70000	40 - 45	2.2	0.06
30.09. 2009	ALTM 3100	1100	20	70000	31 - 66	2.7	0.05
08.10. 2010	ALTM Gemini	1000	25	70000	62	3.6	0.03
04.10. 2011	ALTM 3100	1100	20	70000	25 - 75	2.9	0.04

Table 2: Area averaged annual altitudinal changes $\overline{\Delta z}$ (m) and according standard deviation SDΔz (m) of selected stable areas in the surroundings of Hintereisferner. Bold numbers indicate the existence of snow cover.

		Δz campaign [m]	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11
Stable areas	A ~3000 m a.s.l.	$\overline{\Delta z}$ stable area (A)	**-0.38**	-0.10	0.00	**0.13**	**-0.58**	**-0.17**	**-0.26**	0.03	0.15	-0.06
		SDΔz surface lowering A	0.03	0.04	0.03	0.06	0.09	0.12	0.06	0.02	0.04	0.03
	B ~3100 m a.s.l.	$\overline{\Delta z}$ stable area (B)	**-0.42**	-0.14	-0.02	**0.17**	**-0.52**	**-0.16**	**-0.18**	0.04	0.10	-0.05
		SDΔz surface lowering B	0.09	0.03	0.07	0.06	0.12	0.08	0.03	0.03	0.09	0.01
	C ~3200 m a.s.l.	$\overline{\Delta z}$ stable area (C)	**-0.46**	-0.15	-0.06	-0.06	**-0.45**	**-0.19**	-0.07	0.10	0.15	-0.10
		SDΔz surface lowering C	0.12	0.02	0.05	0.09	0.07	0.11	0.01	0.04	0.04	0.03
	D ~2500 m a.s.l.	$\overline{\Delta z}$ stable area (D)	-0.14	-0.07	-0.03	0.03	-0.09	-0.01	-0.06	0.05	0.05	-0.11
		SDΔz surface lowering D	0.06	0.07	0.02	0.02	0.07	0.05	0.07	0.03	0.03	0.04
	E ~2850 m a.s.l.	$\overline{\Delta z}$ stable area (E)	**-0.19**	-0.04	-0.04	0.05	**-0.39**	-0.06	-0.01	-0.02	0.10	-0.13
		SDΔz surface lowering E	0.03	0.02	0.03	0.06	0.07	0.05	0.06	0.05	0.03	0.03

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Table 3: Original (WGMS) and area adjusted (εarea) and uncertainty assessed (σglac) annual glaciological mass balances (bglac.hom) in comparison to the - DTM uncertainty (σDTM) assessed - raw annual geodetic mass balances (bgeod.raw); converted into meter water equivalent (m w.e.) using 900 kg m-3), for Hintereisferner from 2001 to 2011.

Period	$\mathbf{b_{glac.WGMS}}$	$\boldsymbol{\varepsilon_{area}}$	$\mathbf{b_{glac.hom}}$ $\pm\sigma_{glac}$	$\mathbf{b_{geod.raw}}$ $\pm\sigma_{DTM}$	$\mathbf{b_{glac.hom}} - \mathbf{b_{geod.raw}}$
2001/02	-0.647	+0.023	-0.624 ±0.21	-1.049 ±0.15	0.425
2002/03	-1.814	+0.018	-1.796 ±0.21	-3.285 ±0.08	1.489
2003/04	-0.667	+0.016	-0.685 ±0.21	-0.509 ±0.09	-0.176
2004/05	-1.061	+0.039	-1.033 ±0.21	-0.650 ±0.16	-0.383
2005/06	-1.516	+0.023	-1.493±0.21	-2.487 ±0.17	0.994
2006/07	-1.798	-0.015	-1.813±0.21	-1.404 ±0.10	-0.409
2007/08	-1.235	-0.011	-1.246 ±0.21	-1.369 ±0.10	0.123
2008/09	-1.182	0.000	-1.182 ±0.21	-1.141 ±0.09	-0.041
2009/10	-0.819	+0.027	-0.792 ±0.21	-0.430 ±0.09	-0.362
2010/11	-1.420	-0.003	-1.423 ±0.21	-1.629 ±0.06	0.206
01/11	-12.159	+0.117	-12.042 ±0.65	-13.343 ±0.14	1.301
01-11$_{\mathbf{cum}}$	-12.159	+0.117	-12.042 ±0.65	-13.953 ±0.36	1.911

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Table 4: Summary of ALS and closest field survey dates of Hintereisferner, mean snow cover in DTM ($\overline{SC}_{ALS}$) and in field survey ($\overline{SC}_{field}$) used for DTM correction, values of survey date adjustments (ε_{survey}), glacier area (A) and classified firn area (AF). Short comments are taken from field measurement minutes. The mean accumulation area decreased from 3.85 km² to 1.98 km² for the period 2001–2011.

ALS survey	field survey	$\overline{SC}_{ALS}$ [m]	$\overline{SC}_{field}$ [m]	ε_{survey} [m w.e.]	A [km²]	A_F [km²]	Comments
11 Oct 2001	8 Oct 2001	0.52	0.47	-0.12	8.02	3.85	Continuous snow cover at field survey (10 – 50 cm, probings < 3400 m a.s.l.); further snowfall between 8th and 11th of October; snow cover estimation based on ALS data
18 Sept 2002	2 Oct 2002	0.00	0.17	+0.08	7.86	3.53	Continuous snow cover at field survey (10 – 35 cm, < 3400 m a.s.l.), snow cover estimation based on field survey and meteorological data
26 Sept 2003	30 Sept 2003	0.00	0.00	-0.02	7.66	3.12	Strong ablation on stakes between 16th August and 30th September; 1 – 4 cm/d below 3000 m a.s.l. estimated based on field survey and meteorological data ; no snow cover at geodetic survey
5 Oct 2004	30 Sept 2004	0.23	0.23	+0.05	7.61	3.05	Continuous snow cover at field survey (5 – 40 cm, < 3400 m a.s.l.); snow cover estimation based on field survey data
12 Oct 2005	30 Sept 2005	0.46	0.30	-0.07	7.51	2.72	Continuous snow cover at field survey (1 – 30 cm, < 3400 m a.s.l.); additional snowfall event between 1st and 12th of October (103 mm on HEF) snow cover estimation based on ALS data
8 Oct 2006	30 Sept 2006	0.13	0.00	-0.01	7.38	2.43	No snow cover at field survey; snowfall events between 3rd and 8th of October (82 mm on HEF); snow cover estimation based on ALS data
11 Oct 2007	1 Oct 2007	0.12	---	-0.01	7.28	2.32	No field survey data available; snowfall events between 1st and 12th of October; snow cover estimation based on ALS data
9 Sept 2008	30 Sept 2008	0.00	0.18	-0.05	7.15	2.03	Continuous snow cover at field survey (0 – 32 cm, < 3400 m a.s.l.; 4 – 28 cm ablation at stakes between 9th and 30th of September; snow cover estimation based on field survey and meteorological data
30 Sept 2009	27 Sept 2009	0.00	0.00	0.00	7.05	2.01	No correction necessary; no significant snow cover < 3400 m a.s.l.
8 Oct 2010	27 Sept 2010	0.26	0.26	-0.03	6.88	2.22	Continuous snow cover at field survey (1 – 42 cm, < 3400 m a.s.l.; snowfall event between 28th of Sept and 8th of October (12 mm on HEF) but nearly no ablation; snow cover estimation based on field data
4 Oct 2011	4 Oct 2011	0.00	0.00	0.00	6.79	1.98	No correction necessary; no significant snow cover < 3400 m a.s.l.

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Table 5: Quantified method-inherent differences and uncertainties related to DTM (εDTM and σDTM), density conversion (εκ and σκ), survey dates (εsurvey), internal processes (εint and σint) and crevasse volume (εcrev). While the overall εgeod accumulates from all individual differences, the overall σgeod is calculated by propagating the individual uncertainties. All units are in meter water equivalent (m w.e.), except of the dimensionless κ.

year	κ	ε_{DTM}	ε_{κ}	ε_{survey}	ε_{int}	ε_{crev}	ε_{geod}	σ_{DTM}	σ_{κ}	σ_{int}	σ_{geod}
01/02	830±30	+0.29	+0.08	-0.03	+0.05	-0.02	+0.36	±0.15	±0.04	±0.015	±0.16
02/03	820±45	+0.09	+0.31	+0.06	+0.05	+0.06	+0.57	±0.08	±0.18	±0.015	±0.20
03/04	875±20	-0.20	+0.01	+0.03	+0.05	-0.04	-0.15	±0.09	±0.01	±0.015	±0.09
04/05	855±30	-0.41	+0.03	-0.02	+0.05	-0.04	-0.38	±0.16	±0.02	±0.015	±0.17
05/06	850±35	+0.29	+0.14	-0.08	+0.05	-0.005	+0.40	±0.17	±0.10	±0.015	±0.19
06/07	885±20	-0.02	+0.02	-0.02	+0.05	+0.004	+0.04	±0.10	±0.01	±0.015	±0.10
07/08	865±25	+0.10	+0.05	-0.06	+0.05	-0.02	+0.12	±0.10	±0.04	±0.015	±0.11
08/09	890±20	-0.05	+0.01	-0.05	+0.05	-0.03	-0.07	±0.09	±0.02	±0.015	±0.10
09/10	930±20	-0.32	-0.03	-0.03	+0.05	-0.04	-0.37	±0.09	±0.02	±0.015	±0.09
10/11	870±25	+0.32	+0.05	+0.03	+0.05	-0.02	+0.43	±0.06	±0.04	±0.015	±0.07
01/11	890±20	+0.29	+0.13	-0.07	+0.50	+0.05	+0.77	±0.14	±0.27	±0.047	±0.20
cum	---	+0.11	+0.69	-0.18	+0.50	-0.15	+0.28	±0.36	±0.22	±0.047	±0.78

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Table 6: Summary of the statistical comparison of glaciological and geodetic balances of Hintereisferner. The table shows different periods of record with the improved balances (b_{geod}; b_{glac}) and related method-inherent uncertainties (±σ), together with differences ($\Delta b = b_{glac} - b_{geod}$), common variance ($\varepsilon_{comvar}$), and the statistical significance δ. The acceptance of the null-hypothesis (H_0), whether the glaciological balance is statistically different from the geodetic balance or not, is evaluated on the 95% confidence level, which corresponds to δ-values inside (outside) the ±1.96 range, respectively. β depicts the probability of accepting H_0 inspite of differences at the 95% confidence level.

Period	**b_{geod} ±σ [m w.e.]**	**b_{glac} ±σ [m w.e.]**	**Δb [m w.e.]**	**σ_{comvar} [m w.e.]**	**δ no unit**	***H_0*: 95 no unit**	***β*: 95 [%]**
2001/2002	-0.685 ± 0.16	-0.624 ± 0.21	+0.061	0.26	0.24	yes	94
2002/2003	-2.713 ± 0.20	-1.796 ± 0.21	+0.917	0.29	3.21	**no**	11
2003/2004	-0.654 ± 0.09	-0.651 ± 0.21	+0.003	0.23	0.01	yes	95
2004/2005	-1.028 ± 0.17	-1.022 ± 0.21	+0.006	0.27	0.02	yes	95
2005/2006	-2.091 ± 0.19	-1.493 ± 0.21	+0.598	0.28	2.11	**no**	44
2006/2007	-1.363 ± 0.10	-1.813 ± 0.21	-0.450	0.23	-1.97	**no**	50
2007/2008	-1.252 ± 0.11	-1.246 ± 0.21	+0.006	0.23	0.03	yes	95
2008/2009	-1.209 ± 0.10	-1.182 ± 0.21	+0.027	0.23	0.12	yes	95
2009/2010	-0.798 ± 0.09	-0.792 ± 0.21	+0.006	0.22	0.03	yes	95
2010/2011	-1.249 ± 0.07	-1.423 ± 0.21	-0.174	0.22	-0.79	yes	88
01/11	-12.45 ± 0.20	-12.04 ± 0.65	+0.41	0.29	1.44	yes	70
01-11cum	-12.99 ± 0.78	-12.04 ± 0.65	+0.95	0.81	1.18	yes	78