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RECENT GLACIER CHANGES AND RELATED CONTRIBUTION POTENTIAL TO RIVER DISCHARGE IN THE VINSCHGAU / VAL VENOSTA, ITALIAN ALPS

Abstract: Galos S.P., Klug Ch., Prinz R., Rieg L., Dinale R., Sailer R. & Kaser G., *Recent glacier changes and related contribution potential to river discharge in the Vinschau/Val Venosta, Italian Alps.* (ITISSN, 0391-9838).

Recent glacier changes in the Vinschgau / Val Venosta region of the Autonomous Province of Bozen / Bolzano, Northern Italy, were quantified using high resolution multi-temporal airborne laser scanning data (fall 2005 to fall 2013). The analysis reveals a marked reduction in glacier area (-14.6 %), mean surface elevation (-7.1 m) and mass (-388 ± 26 × 10^9 kg) during the study period. Observed values of relative area change and mean changes in surface elevation are similar in the Ötztal Alps and the Texel Group in the North and the Ortler-Cevedale Group in the South of the study region.

The mass balance record of Langenferner / Vedretta Lunga, a well measured glacier within the study region, was analyzed in terms of its representativeness for glacier changes in the wider region. The inter-annual variability of the mass balance signal was investigated by comparing the results to those of other monitored glaciers in the Eastern Alps and the magnitude of the geodetically derived mass change of the glacier was compared to the mass change of all other 91 glaciers within the study region. Results show that Langenferner / Vedretta Lunga over all satisfactorily represents the temporal variability of regional glacier mass changes, but values for the mass balance in certain years request further analysis. Furthermore, the glacier displays one of the most negative values of geodetic mass balance within the study region.

Finally, a first order quantification of glacier melt contribution to total river discharge in the study area is provided which reveals that the annual contribution of excess melt due to glacier retreat amounts to 4.6 % of total river discharge, while values for single years can reach 9 %. During the months July to September, the contribution of glacier melt to total runoff can be in the order of 25 % in single years.

Key Words: Glacier mass balance, Airborne laser scanning, Geodetic mass balance, Glacier runoff, Vinschgau – Val Venosta, Italian Alps.

Riassunto: Galos S.P., Klug Ch., Prinz L., Rieg L., Dinale R., Sailer R. & Kaser G., *Cambiamenti glaciali recenti e relativi potenziali contributi alle portate fluviali nella Vingschau/ Val Venosta, Alpi Italiane.* (IT ISSN 0391-9838).

I recenti cambiamenti glaciali nella Vinschgau/Val Venosta nel territorio della Provincia Autonoma di Bolzano nell'Italia Settentrionale sono stati quantificati con i dati acquisiti mediante l'uso di un Laser Scanning aereotrasportato ad alta risoluzione dall'autunno 2005 all'autunno 2013. Le analisi hanno rivelato una marcata riduzione delle masse glaciali (-14,6 %), della media dell'altezza della superficie (-7.1 m) e della massa (-388 ± 26 % 10^9 kg) nel periodo studiato. I valori osservati delle variazioni dell'area e delle variazioni medie dell'altezza della superficie sono simili nelle Alpi dell'Otztal e nel Gruppo di Tessa a nord e nel Gruppo Ortles-Cevedale a sud dell'area studiata.

Il bilancio di massa del Ghiacciaio del Langenferner / Vedretta Lunga, un ghiacciaio ben misurato nella regione di studio, è stato analizzato in termini di rappresentatività dei cambiamenti glaciali dell'area più vasta. La variabilità interannuale dei bilanci di massa è stata analizzata mettendo a confronto i risultati con quelli di altri ghiacciai monitorati nelle Alpi Orientali. La grandezza dei cambiamenti di massa glaciale ottenuti per via geodetica sono stati comparati con quelli degli altri 91 ghiacciai presenti nella regione. I risultati mostrano che complessivamente il Ghiacciaio del Langenferner / Vedretta Lunga rappresenta in maniera soddisfacente la variabilità temporale dei cambiamenti di massa glaciali nella regione, anche se i cambiamenti di alcuni anni vanno ulteriormente analizzati. Di più, il ghiacciaio mostra uno dei valori più negativi dei bilanci di massa geodetici dell'intera regione studiata.

Infine viene fornito un primo ordine di grandezza del contributo dello scarico glaciale alle portate dei corsi d'acqua delle regione. Il risultato è che il contributo dell'eccesso di scarico dovuto al ritiro glaciale ammonta

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al 4.6 % della portata dei corsi d'acqua mentre i valori di alcuni anni può raggiungere il 9%. Durante i mesi da Luglio a Settembre il contributo dello scarico glaciale può in alcuni anni raggiungere il 25%.

Termini Chiave: Bilancio di massa glaciale, Laser Scanning, Bilancio di massa geodetico, Bilancio idrico,Vinschau/ Val Venosta, Alpi.

INTRODUCTION

During recent decades retreating mountain glaciers around the world have received much attention as they are among the most striking signs of ongoing global climate change (e.g. Vaughan & *alii*, 2013; Marzeion & *alii*, 2014; Zemp & *alii*, 2015) and they represent the second largest contribution to current sea level rise after the thermal expansion of the oceans (Church & *alii*, 2013). Mountain glaciers can also constitute an important component of the local or regional seasonal hydrological cycle and in certain regions of the world they provide a substantial fraction of the available water resources to the local population (e.g. Immerzeel & *alii*, 2010; Kaser & *alii*, 2010). This also holds for some regions in the European Alps (e.g. Schaefli & *alii*, 2007; Lambrecht & Mayer, 2009; Huss, 2011) where the rate of glacier retreat during recent decades was especially strong (e.g. Paul & *alii*, 2004; Lambrecht & Kuhn, 2007; Fischer & *alii*, 2014). One of these regions is in the focus of the current study: Vinschgau / Valle Venosta, a dry inner alpine catchment in the central Eastern Alps with a relatively high degree of glaciation.

The rapid glacier changes within the Eastern Alps during recent decades were addressed by a range of studies (e.g. Carturan & *alii*, 2013a; Scotti & *alii*, 2014), which resulted in a number of national or regional glacier inventories or similar data sets (e.g. Abermann & *alii*, 2009; Knoll & Kerschner, 2009; Fischer & alii, 2014). However, these studies do not address regional scale glacier change in the Vinschgau / Valle Venosta during the recent decade, nor do they provide a quantification of the consequent contribution of observed glacier melt to the water availability in this region.

The relevance of glacier melt runoff for the (sub-) seasonal water availability in the Vinschgau / Valle Venosta is under investigation within a scientific project at the University of Innsbruck in cooperation with the Hydrological Office Bozen / Bolzano. As part of this project and as a first step towards more detailed future analyses, the goals of the current study are (i) a sound quantification of recent glacier changes within the study region during the period 2005 to 2013 using high resolution airborne laser-scanning data, (ii) the evaluation of the regional representativeness of Langenferner / Vedretta Lunga (LGF), a well measured glacier within the study region, and (iii) a first order estimate on the contribution of glacier melt to total river discharge.

STUDY SITE

The Vinschgau / Val Venosta

The Vinschgau / Val Venosta (fig. 1) is situated in the Italian part of the central Eastern Alps and covers an area of about 1500 km². Four percent of the catchment is covered by glaciers. The valley is shielded from synoptic precipitation by the surrounding high mountain ranges of the Ötztal Alps and the Texel Group in the North, the Sesvenna Group in the Northwest, the Bernina and Livigno Alps in the Southwest and the Ortler-Cevedale Group in the South. Consequently, with annual precipitation amounts of ~ 500 mm or less at the bottom of the main valley, Vinschgau / Val Venosta is one of the driest areas within the European Alps (e.g. Frei & Schär, 1998). About one third of the precipitation in the study region falls during summer (June, July, August), often related to convective events leading to an increased frequency of precipitation compared to the rest of the year (e.g. Fliri, 1976; Adler & *alii*, 2015). Winter precipitation, which forms the largest part of glacial accumulation, is mainly associated with southwesterly air flow, triggered by cyclonic activity over the Mediterranean Sea (e.g. Auer & *alii*, 2007; Frei & Schär, 1998). Only a minor part of the annual precipitation amount is related to fronts from northern directions. Due to the dry climate, sunshine duration and air temperature are higher than in other Alpine regions (e.g. Adler & *alii*, 2015). The mean zero-degree level in the study region derived from high altitude weather stations (2004 - 2013) is around 2500 m a.s.l.

The main water resources of the valley are the Etsch / Adige River and its tributaries which during the ablation period are fed by the melt runoff of about 100 glaciers and glacierets. The water of these rivers is partly used for fruit cultivation in large orchards which, in addition to tourism, is the dominant economic activity in the region. As large amounts of water are used for irrigation during the growing season, the contribution of glacier melt to the total river discharge can be of considerable importance for the local water availability and economic activity during dry and hot periods in summer (e.g. Schaefli & *alii*, 2007; Lambrecht & Mayer, 2009).

Langenferner / Vedretta Lunga

Situated at the head of Martell / Martello Valley in the Ortler-Cevedale Group, Autonomous Province of Bozen / Bolzano, Northern Italy, LGF (46.46°N|10.61°E) is a small valley glacier where detailed glaciological measurements have been carried out since the hydrological year 2003/04. As other long term glacier monitoring programs in the region (Careser since 1967 and Weißbrunnferner / Fontana Bianca since 1984) seem to be (i) threatened by the massive glacier retreat during the recent decades (e.g. Carturan & *alii*, 2013b) and/or (ii) are considered to be of limited regional representativeness (Kaser & *alii*, 1996; Carturan & *alii*, 2013a), the LGF program was initiated in order to create a new long term monitoring site allowing the temporal extension of glaciological measurements within this region into the upcoming decades. The glacier is part of the large glaciated area surrounding the Cevedale Massif, in addition to LGF consisting of Fürkele Ferner / Ved. della Forcola, Zufallferner / Ved. del Cevedale, Vedretta de la Mare and Vedretta di Cedec.

Fig. 1 - Satellite-image of the study region showing LGF in red and other observed glaciers in yellow. The Ötztal Alps (OEA) and Texel Group (TSG) are situated in the North, the glaciers of the Ortler-Cevedale Group (OCG) in the South of the study region. The political outline of Vinschgau / Valle Venosta is indicated by the red line while the area shown in Figure 3 is given by the green rectangle and the location of the runoff gauge in Töll / Tel is shown by a green dot.
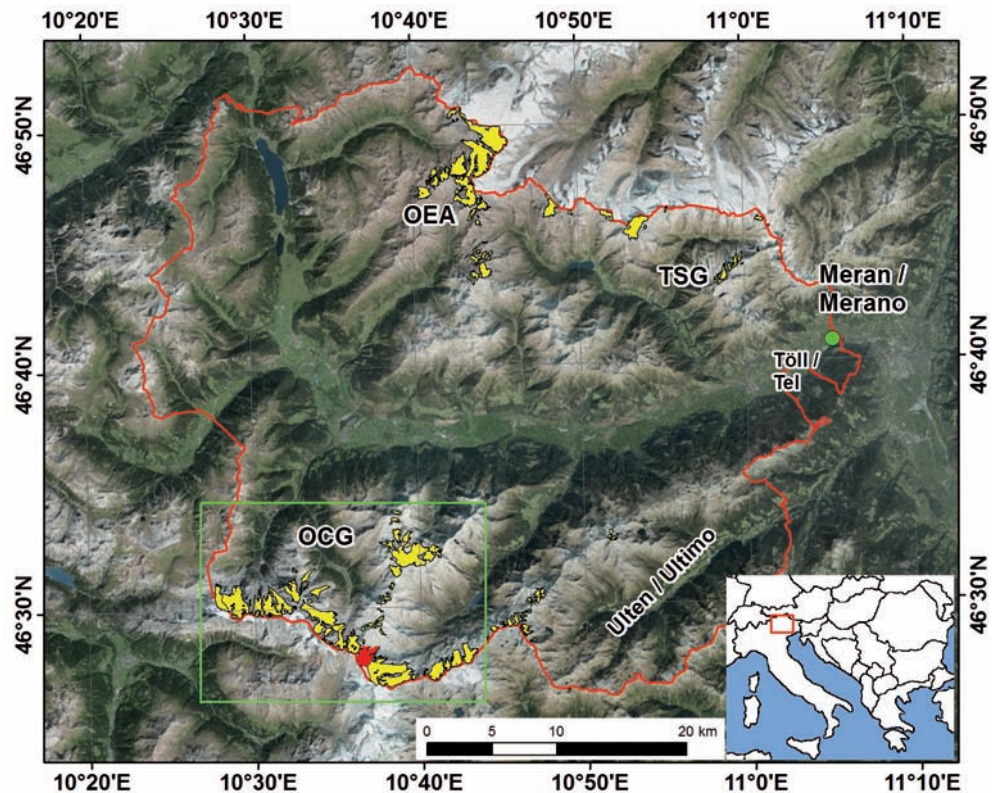
The highest point of LGF (fig. 2) is defined by an ice divide which was derived by applying a watershed algorithm (e.g. Winsvold & *alii*, 2014) to the glacier surface topography obtained by photogrammetry in 1996. Although the surface topography in this area changed during the observation period due to considerable glacier recession, the impacts on the glacier flow direction are negligible and the outlines of the uppermost glacier part were consequently kept constant throughout the study period. In 2013, the highest point of LGF was at 3370 m a.s.l., while the terminus elevation was 2711 m a.s.l. The glacier area at that time amounted to 1.61 km² with a median altitude of about 3143 m a.s.l. The upper part of LGF is exposed to the North while the lower sections face East. The glacier runoff feeds the Plima River, which is a tributary to the Etsch / Adige. Ground penetrating radar measurements carried out by the Institute of Atmospheric & Cryospheric Sciences / University of Innsbruck (ACINN) in spring 2010 gave an estimated glacier volume of 0.08 km³ with a maximum thickness of about 130 m in the upper glacier part, between Rifugio Casati and the Tre Cannoni (fig. 2).

Since its Little Ice Age maximum extent around the year 1822 (Finsterwalder, 1890), the tongue of LGF has retreated by more than 3 km and during recent decades the glacier was among the fastest retreating glaciers in Italy (e.g. Baroni & *alii* 2013; WGMS, 2012 and earlier volumes). Figure 2 illustrates the glacier retreat in area since 1996, which amounts to 0.57 km² (-26%).

DATA AND METHODS

Airborne laser scanning and orthophotos

Regional changes in glacier area and volume during the period 2005 to 2013 were derived using multi-temporal airborne laser scanning (ALS) data which has proven to be a powerful tool to detect and quantify glacier changes (e.g. Geist & *alii*, 2003; Abermann & *alii*, 2010; Joerg & *alii*, 2012). In the current study the analyses are based on data from two ALS campaigns. The first campaign (ALS1) was commissioned by the Autonomous Province of Bozen / Bolzano in 2005 (Zanvettor & *alii*, 2006) and has a mean point density of 1.06 points per m² within the study area. The exact dates of the survey unfortunately were not documented, but a comparison with field data suggests an acquisition date around the mid of September 2005. The second data acquisition (ALS2) was performed on September 22nd and 23rd 2013, except for the glaciers in the Schnals / Senales tributary valley which were surveyed on September 5th. The mean point density of ALS2 is 2.65 points per m². High resolution (1 m) digital elevation models (DEM) calculated from the ALS point cloud data provided the basis for the subsequent analyses. The vertical error of the DEMs was tested by investigating the DEM differences in stable areas with low slope angles (<30°). The resulting mean squared vertical error amounts to 0.12 m with a standard deviation of 0.21 m and a nearly Gaussian error distribution. The error is increasing in steeper terrain, but this is not really relevant for our study, since only a minor
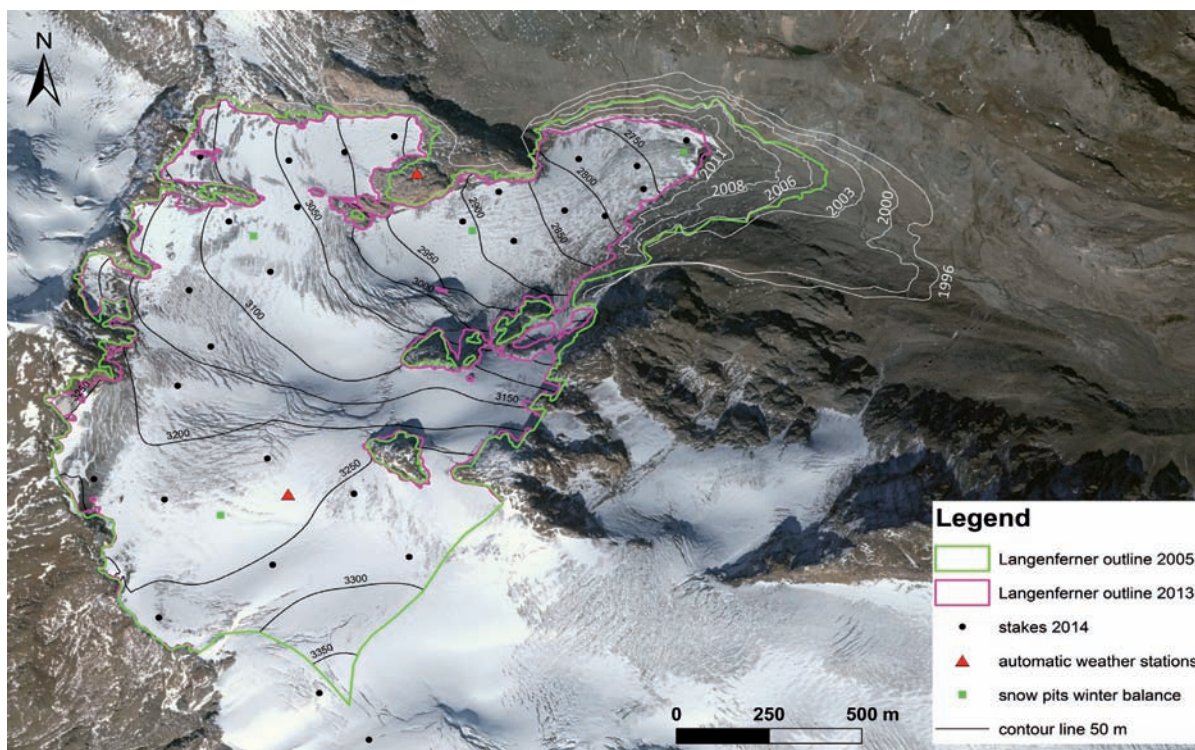
Fig. 2 - Orthophoto of 2012 showing the mass and energy balance measurement network at LGF. Glacier outlines from years when orthophotos or ALS data are available illustrate areal glacier retreat since 1996. (Orthophoto source: World Imagery - Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community)

fraction of the investigated glacier areas display slope angles steeper than 30°.

The glacier outlines for both dates were delineated from high resolution hill shade DEMs following the approach of Abermann & *alii*, 2010. Orthophotos from the years 2006 and 2012 offered additional information for the delineation procedure. The Orthophotos for 2006 were provided by the Autonomous Province of Bozen / Bolzano, while those for 2012 are available through ESRI - ArcGis World Imagery. In the case of the heavily debris covered Suldenferner we also benefit from in situ observations conducted in the frame of another scientific project at the ACINN.

Changes in glacier surface elevation were derived based on differencing the obtained DEMs for the glaciated areas (e.g. Geist & Stötter, 2007; Abermann & *alii*, 2010). As all investigated glaciers displayed a retreating behavior during the study period, we used the larger glacier extents of 2005 as the reference area for the subsequent calculations. To calculate volume changes, the elevation differences for single grid cells were multiplied by the cell size (1 x 1 m) and integrated over the area of the respective glacier. Mass changes were then calculated by multiplying volume changes with the density range of 850 ± 60 kg/m³ as proposed by Huss (2013). This wide range of density was applied in order to account for the uncertainties related to the regional scale volume-to-mass conversion such as the unknown spatial extent of firn areas and crevasse zones.

MASS BALANCE MEASUREMENTS AT LANGENFERNER / VEDRETTA LUNGA

Annual surface mass balance studies at LGF have been carried out since the hydrological year 2003/04 by the ACINN in collaboration with the Hydrological Office Bozen / Bolzano applying the direct glaciological method with the fixed date convention (e.g. Østrem & Brugmann, 1991; Kaser & *alii*, 2003). In all observation years, measurements were performed close to the end of the hydrological year (between September 28th and October 8th) except for 2005 and 2007, when unfavorable weather conditions led to a delay of a few days. Whenever required, corrections for snow accumulation were applied to obtain the fixed date mass balance. Corrections for ablation were not necessary as in that time of the year considerable glacier melt commonly coincides with fair weather conditions during which measurements were performed.

Winter balance measurements follow the floating date system and have been conducted each year at the beginning of May (in all years between May 2nd and 18th) performing about 50 to 100 snow depth probings and normally four density pits. During summer, ice ablation is measured at 29 (2013/14) ablation stakes which are read up to six times a year depending on location and current conditions. Accumulation at the end of the hydrological year is measured in one or two snow pits accompanied by a number of snow depth

probings depending on the amount and spatial extent of present snow. Figure 2 gives an overview on the measurement network at LGF.

The point values of specific mass balance have been manually extrapolated to the area of the whole glacier applying the contour line method (e.g. Østrem & Brugmann, 1991) using additional information such as repeated terrestrial and airborne photos giving the spatial distribution of snow covered areas and the date of the onset of ice ablation. Further analyses such as spatial integrations and intersections with altitudinal bands and the final calculations of the mean specific mass balance were performed in ArcGIS. Respective data for glacier outline and topography for the first observation years originate from stereo-orthophotos of the year 1996. The glacier outline was updated in 2005 using data from a survey with a differential geo-positioning system (DGPS). Since the hydrological year 2007/08 analyses were based on the ALS data of 2005 with another DGPS update for the glacier outline in 2010. During recent years, glacier topography and outlines were updated using ALS data of the years 2011 (since 2011/12) and 2013 (2013/14). The results of the mass balance program at LGF (fig. 4) are reported to the World Glacier Monitoring Service (WGMS).

Runoff data

Monthly values of river discharge for the Etsch / Adige River measured at the village of Töll / Tel in the lowest part of the study area were provided by the Hydrological Office of Bozen / Bolzano. The discharge of 98.9 % of the observed glacier area in the study region is captured by this station. The remaining 1.1 % drain to the Ultental / Val d'Ultima and enter the Etsch / Adige further downstream. In our analysis the mass change of these glaciers is considered to compensate for a few small glacierets within the catchment of Töll / Tel which are not captured by our analysis due to the lack of data in ALS2.

RESULTS AND DISCUSSION

Regional changes in glacier area, volume and mass

Changes in glacier area, thickness, volume and mass were calculated for 92 individual glaciers and glacierets in the study region for the period September 2005 to September 2013. The total area of the observed glaciers amounts to 64.3 km² for the year 2005 and has reduced by 14.6 % to 54.9 km² until 2013. Significant areal shrinkage was detected for all glaciers in the region. None of the observed glaciers displayed a stationary or advancing behavior during the study period. The mean area loss in the Southern Ötztal Alps (29 glaciers, 36 % of observed glacier area) during the study period (2005 to 2013) was 15.5 %, while retreat in the Ortler-Cevedale Group (55 glaciers, 63 % of observed glacier area) amounts to 14.0 %. As demonstrated in other studies (e.g. Abermann & *alii*, 2009; Carturan & *alii*, 2013a), smaller glaciers tend to lose larger fractions of their total extent which explains the larger relative area loss of 20.2 % observed in the Texel Group (8 glaciers, 1 % of observed glacier area).

All observed glaciers showed a decrease in mean surface elevation. At the lower parts of some valley glaciers the observed reduction in surface elevation is in the order of 25 to 40 m. Highest rates of surface elevation loss were observed in the lower parts of Langtauferer Ferner / Ghiacciaio di Vallelunga, Fürkele Ferner / Ved. della Forcola, Zufallferner / Ved. del Cevedale and LGF. Small reductions or even some areas with increasing surface elevation were detected in areas where avalanche accumulation is significant, for example around Königsspitze / Grand Zebru or in parts of Oberer Ortlerferner / Alto dell Ortles (fig. 3), which as a whole showed the smallest change of mean surface elevation (-2.2 m) of all glaciers. Remarkable is the detection of a widespread reduction of glacier thickness even in the highest glaciated parts of the study region (fig 3). The mean change in glacier surface elevation for the whole study area amounts to -7.1 m which corresponds to a mean change rate of about -0.9 m per year. There is no significant difference between glaciers in the Ötztal Alps (-7.2 m), the Texel Group (-6.7 m) or in the Ortler-Cevedale Group (-7.1 m).

The detected volume loss integrated over all glaciers in the study region amounts to 0.46×10^9 m³. In order to calculate the corresponding mass loss, the density range of 850 ± 60 kg/m³ proposed by Huss (2013) was applied to the derived volume loss. The resulting change in glacier mass amounts to $-388 \pm 26 \times 10^9$ kg and is distributed between the different mountain ranges as follows: Ötztal Alps: $-140 \pm 9 \times 10^9$ kg, Texel Group: $-8 \pm 0.6 \times 10^9$ kg, Ortler-Cevedale Group: $-240 \pm 16 \times 10^9$ kg.

Many of the observed glaciers showed signs of strong imbalance with current climate conditions such as rapid terminus retreat, down-wasting and areal shrinking, disintegration into smaller component parts, an increasing number and size of rock outcrops and an increase of debris covered areas. Similar observations have recently been reported from neighboring mountain ranges (e.g. Abermann & *alii* 2009, Carturan & *alii* 2013a, D'Agata & *alii*, 2014).

Uncertainties of regional data

While the ALS derived surface elevation data is of high accuracy (vertical accuracy of 0.12 m compared to an observed mean glacier surface elevation change of -7.1 m), the main error sources in this study are related to the delineation of glaciated areas, the extent and amount of snow cover and the conversion of glacier volume change to mass change.

One of the key difficulties in determining glacier outlines is associated with delineating the margins of debris covered ice areas. In the current study, glacier outlines were delineated on the basis of maps of surface elevation difference between ALS1 and ALS2 in which non-glaciated terrain is readily identifiable as having undergone no vertical change. This approach minimizes respective errors (Abermann & *alii*, 2010), and hence enables a relatively accurate determination of glacier areas, especially for the date of the first data acquisition in fall 2005. Accordingly, the glacier outlines calculated by Knoll & Kerschner (2009) were not used in our study, as their delineation was based on a different technique without DEM-differencing.
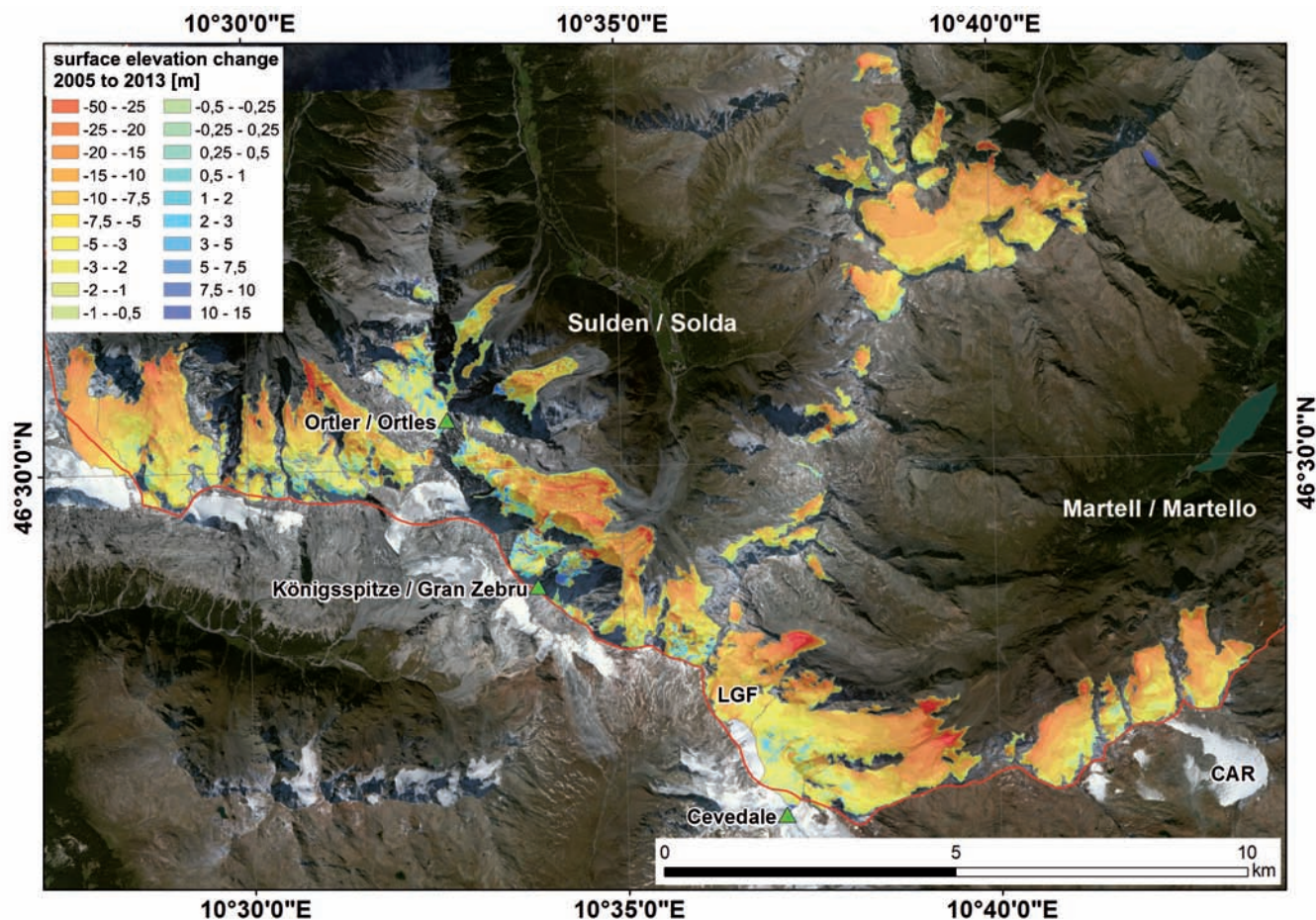
Fig. 3 - Spatial distribution of surface elevation change for glaciers in the Ortler-Cevedale Group. The locations of Langenferner / Vedretta Lunga and Careser are given by the acronyms LGF and CAR respectively. Lower areas of the larger glaciers around Cevedale show the most significant decrease in surface elevation (red areas) while some very high or avalanche dominated glacier parts around Königsspitze / Gran Zebru and Ortler / Ortles display minor changes or even slight increase in surface elevation (green & blue areas).

The largest source of error in our study most probably relates to snow cover which cannot be quantified for individual glaciers within the study area and which is affecting the conversion of the detected changes in surface elevation and volume to changes in mass.

As a consequence of the extremely hot summer 2003, the extent of multi-year firn areas across the region was strongly reduced. Hence, by 2005, the compaction of multi-year firn bodies is unlikely to play a significant role on the regional scale. In addition, the size of those areas did also not change drastically between ALS1 and ALS2. In contrast, the amount of snow cover on the glaciers differed significantly between the dates of ALS1 and ALS2. Field work notes and photos from LGF combined with meteorological information from high elevation weather stations in the study region confirm that at the date of ALS1 (mid of September 2005) the glaciers were covered only with a few centimeters of snow which was restricted to regions above 3000-3200 m a.s.l. At the date of ALS2 (September 2013), the thick-

ness and extent of snow cover on the glaciers in the study region was significantly larger than during ALS1. This was mainly due to the fact that on most glaciers a considerable amount of snow from the previous winter survived throughout the ablation season of 2013. At LGF the accumulation area at the end of the hydrological year 2012/13 accounted for 53 % of the total area, while the mean accumulation area ratio of the years 2004/05 to 2011/12 was about 10 %. In the upper parts of LGF the thickness of the observed snow layer reached the order of two meters. Similar is true for other glaciers in the region (Matscherferner / Gh. di Mazia, Madatschferner / Gh. del Madaccio, Texelferner / Gh. di Tessa) where the ACINN carried out direct measurements in September and October 2013. As a result of the large snow amounts in fall 2013, the derived changes in regional glacier mass are somewhat underestimated. A correction for this problem on the regional scale is difficult and for this qualitative analysis is considered not necessary as we make recourse to the broad range of glacier density proposed

by Huss (2013). Nevertheless, we subsequently provide a quantification of the error related to the 2013 snow cover at LGF.

In fall 2013 snow depth probings at LGF were carried out simultaneously with ALS2 on September 23rd. In combination with further snow depth and density measurements carried out on September 6th and October 1st 2013, this data allow for a sound quantification of snow depth and mass at LGF. In order to calculate the mass of the snow layer we distinguished between snow from the previous winter and snow fallen in late Summer / early Autumn 2013. Point measurements of snow depth were extrapolated to the glacier area by applying an automatic interpolation algorithm. The resulting mean thickness of the snow cover at LGF during ALS2 was 0.79 m ranging from values close to zero in the lower most areas of the glacier tongue to more than two meters in some areas in the upper glacier part. The snow mass was determined by combining the rasters for snow depth with snow density information obtained at LGF on September 23rd (autumn snow) and on October 1st (snow from previous winter). The values used in the subsequent analysis are 500 kg/m³ and 300 kg/m³ for snow of the previous winter and for snow of late Summer / early Autumn 2013 respectively.

The geodetically derived mass change of a glacier can be formulated as follows:

$$\Delta M = \overline{\Delta z} \cdot \overline{\rho}_{gl} + corr_s(ALS_1) - corr_s(ALS_2), \quad (1)$$

where ΔM is the mass change, $\overline{\Delta z}$ is the ALS derived mean change in surface elevation, $\overline{\rho}_{gl}$ stands for the mean glacier density (in our case 850 ± 60 kg/m²), while $corr_s(ALS_1)$ and $corr_s(ALS_2)$ represent the corrections related to snow cover during ALS1 and ALS2 respectively. As previously discussed, we omit the correction for ALS1 due to the fact that the shallow snow cover at the date of ALS1

was negligible in the context of our analysis over a period of eight years with drastic glacier retreat. The snow correction for ALS2 writes as:

$$corr_s(ALS_2) = \overline{H}_s(ALS_2) \cdot \overline{\rho}_{gl} - \overline{H}_s(ALS_2) \cdot \overline{\rho}_s(ALS_2), \quad (2)$$

where $\overline{H}_s(ALS_2)$ is the mean snow depth during ALS2 and $\overline{\rho}_s(ALS_2)$ is the respective mean snow density (444.3 kg/m³). Hence, the mean specific mass of snow cover during ALS2 at LGF ($\overline{H}_s(ALS_2) \cdot \overline{\rho}_s(ALS_2)$) amounts to 351 kg/m² which leads to a value of $corr_s(ALS_2)$ of -321 kg/m². Assuming a density of 850 ± 60 kg/m³, the ALS derived mean specific geodetic mass balance of LGF during the period fall 2005 to fall 2013 (uncorrected for snow) amounts to -9381 ± 663 kg/m². This indicates that the correction for snow cover at LGF during ALS2 changes the result by -3.4 % and that the impact of snow cover is covered by the broad density range we applied.

ANNUAL SURFACE MASS BALANCE AT LANGENFERNER

Results of the direct glaciological observations at LGF for the period 2003/04 to 2013/14 show a mean annual surface mass balance of -1050 kg/m² with persistent mass loss in all years except for the hydrological year 2013/14. Values for single years range from -1637 kg/m² in 2007/08 to +442 kg/m² in 2013/14. Especially the first years of the observation period were characterized by very negative mass balances (fig. 4). The years around 2010 brought a slight decrease of the observed mass losses, while in 2012 ablation rates increased with considerable magnitudes of melt even in the highest glaciated areas of the region. Large amounts of accumulation in late spring / early summer 2013 followed by a relatively short ablation season resulted in limited mass loss on LGF and possibly even in positive mass balances at a few smaller glaciers in the
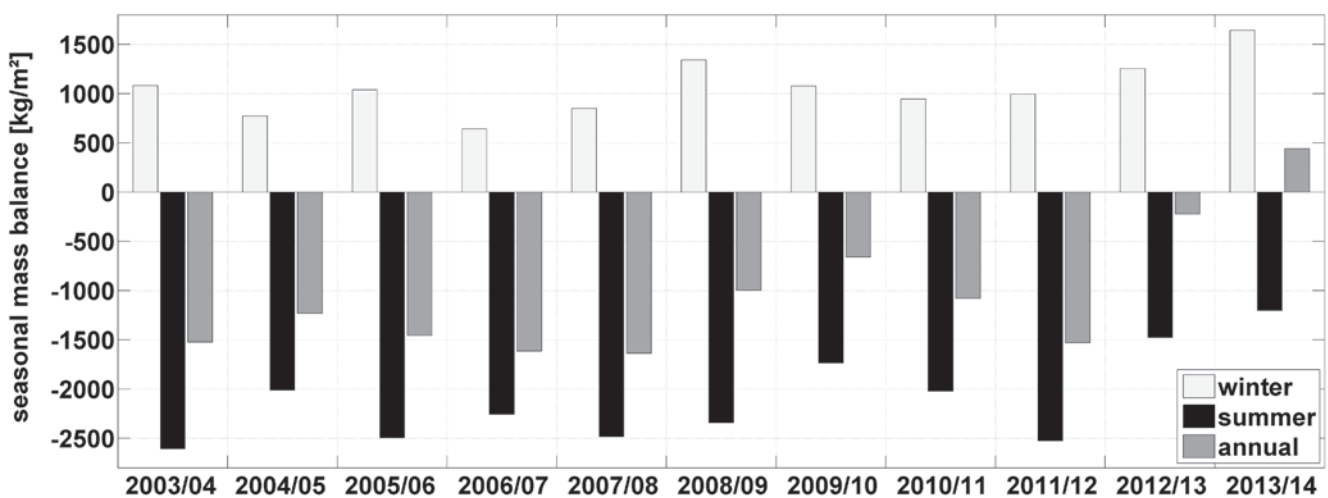

FIG. 4 - Time series of seasonal and annual mean specific mass balances measured at LGF during the period 2003/04 to 2013/14.

region in that year. The exceptionally high accumulation in winter 2013/14 and the following cool (relative to the preceding years) summer 2014 combined to give the only positive mass balance at LGF in the study period. However, the mass gain of 2013/14 compensates for less than 4% of the large mass losses at LGF during the ten preceding years.

REPRESENTATIVENESS OF THE LANGENFERNER RECORD

The mass balance record at LGF comprises eleven years of direct observations, a time span sufficient for first comparisons with records from other mass balance glaciers and further analyses. Hence, we investigated the spatial representativeness of the LGF record regarding both, the magnitude and inter-annual variability of the directly measured annual mass balance. Furthermore the directly measured mass balance was compared to the geodetic mass balance for the period fall 2005 to fall 2013.

A comparison of the directly measured annual mass balance at LGF to the mass balance time series of eight other directly measured glaciers in the Silvretta, the Ötztal Alps, the Stubai Alps and the Ortler-Cevedale Group (fig. 5) shows that the inter-annual variability of the mass balance record at LGF correlates with records of other reference glaciers. Values for the mean specific mass balance at LGF are in most cases around the mean of all other glaciers except for the years 2003/04 and 2007/08 when a shift towards negative values is detectable. Nevertheless, the temporal variability of LGFs rank within the sample set is comparable to those of other individual glaciers. On this basis, it seems reasonable to transfer the temporal

mass balance signal from LGF to other glaciers of the region, despite the local topographic constraints, the effect of area altitude distribution (Kuhn & alii, 1985) and the slight tendency towards a more positive rank towards the end of the study period visible in Figure 5. The latter may partly be explained with the loss of low elevated areas at the formerly larger tongue of the glacier (fig. 2) which were subject to large mass and area losses during the observation years. It may also be worth noting that in the first observation year the mass balance calculations were carried out using the glacier area of 1996 as a reference, which leads to a negative bias of calculated mass balance values. Another source of error may be the lack of measurement points in the upper glacier area during the first observation years affecting the quality of spatial extrapolations. All the afore mentioned problems require further investigations and are hence subject to a follow up study dedicated to the re-analysis of the mass balance record at LGF. Preliminary results of that study show that the largest errors occur in 2003/04 and 2007/08 (fig. 4 and 5), when the amount of surface mass loss is most likely overestimated.

To investigate the regional representativeness of the mass balance magnitude at LGF, the geodetic mass balance of LGF was related to the geodetic mass balance of all other 91 glaciers in the study region. This assessment shows that LGF is amongst the glaciers with the most negative geodetic mass balance during the period fall 2005 to fall 2013, eventhough its altitudinal area distribution is quite representative for the study region (fig 7.) Consequently, a sound extrapolation of specific mass balance values obtained at LGF to the regional scale requires further analyses.
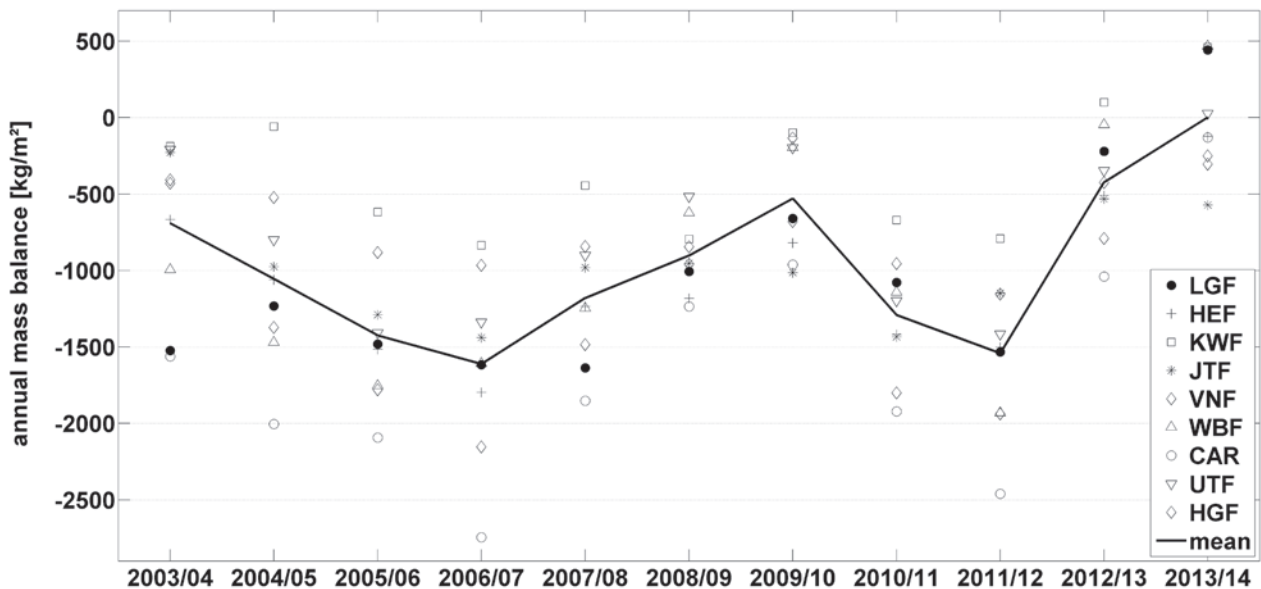

FIG. 5 - The time series of annual mean specific mass balances measured at LGF in relation to mass balance series of eight other glaciers in Eastern Alps: Hintereisferner (HEF), Kesselwandferner (KWF), Jamtalferner (JTF), Vernagtferner (VNF), Weißbrunnferner / Ved. Fontana Bianca (WBF), Careser (CAR), Uebeltalferner / Gh. d. Malavalle (UTF), Hangender Ferner / Ved. Pendente (HGF) and the sample mean.
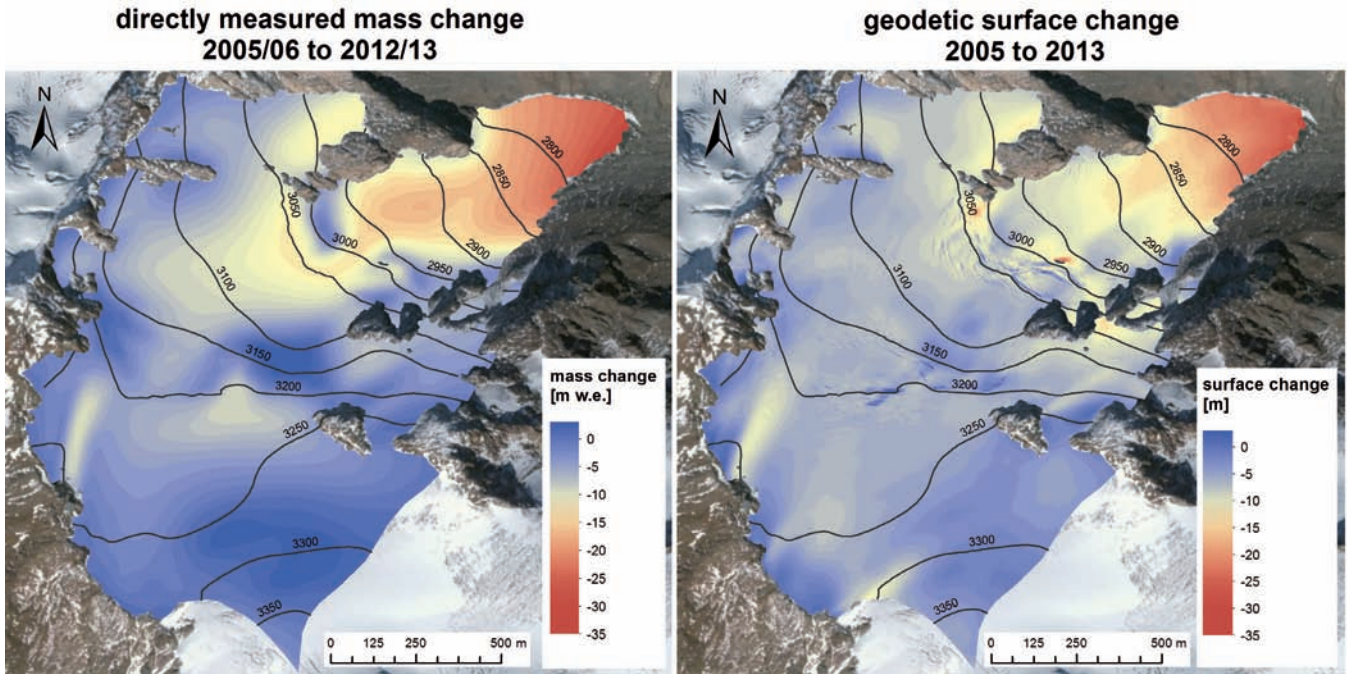
FIG. 6 - Spatial comparison of directly measured surface mass change (left panel) and ALS derived surface height change (right panel) at LGF for the period 2005 to 2013.

To cross-check the magnitude of the directly measured mass balance at LGF, the respective results for the years 2005/06 to 2012/13 were compared to the geodetically derived (from ALS1 and ALS2) mass balance. Figures 6 and 7 show significant differences in the spatial patterns of the two methods, which can be explained as follows: While the directly measured mass balance only accounts for mass change on the glacier surface, the geodetic measurements also capture the local mass change due to glacier dynamics and mass change due to internal or subglacial processes (e.g. Zemp & alii., 2013). Consequently, the mass balance values at a fixed point of the glacier may differ significantly. The spatial pattern of the geodetic mass balance is smoother due to the compensative effect of ice flow. This effect is of course cancelled out by integrating the mass balances obtained by either method over the whole glacier area. At LGF the two methods show satisfying agreement on the glacier-wide scale. While the cumulated mean specific mass balance 2005/06 to 2012/13 calculated from the direct measurements amounts to -9197 kg/m², the geodetic mass balance using a density of 850 ± 60 kg/m³ corrected for 2013 snow cover is -9702 ± 685 kg/m². Since large multiannual firn layers (Huss, 2013), and crevasse zones covering large areas of the glacier are not present at LGF, the magnitude of the geodetic mass loss is most likely slightly underestimated. But as a first order comparison the agreement between the two methods is sufficient and a calibration of the results obtained by the direct method (Zemp & alii, 2013) seems unnecessary.

THE CONTRIBUTION POTENTIAL OF GLACIER MELT TO TOTAL RIVER DISCHARGE

While during steady state conditions glaciers only act as a seasonal storage retaining water during the accumulation period and releasing it during the melt period, in years of glacier retreat they provide an additional contribution to stream flow. In order to provide a qualitative first order analysis of this excess discharge due to glacier retreat within the study area, the regional glacier mass changes were related to the stream flow of the Etsch / Adige measured at the village of Töll / Tel in the lowest part of the study area.

The mean annual excess discharge due to glacier mass loss at Töll / Tel amounts to about 4.6 % (tab. 1). This fraction rises to 12.2 % when considering only the months July, August and September (JAS) during which virtually all the glacier melt occurs (apart from the seasonal on-glacier snow cover). Annual values were obtained by scaling the regional glacier mass change with the series of annual mass change at LGF. The transfer of mass balance properties from one glacier to another or even to the regional scale is complex and difficult (e.g. Kuhn & alii, 2009; Huss, 2012) so this simplified analysis is error prone. Consequently, this problem will be addressed in more detail in a follow-up study including distributed glacier modeling and our analysis presented here can be regarded as a first order approximation. As such, the obtained values for annual runoff contribution are listed in Table 1. Numbers vary between 0.8 % in the hydrological year 2012/13 and 9 % in the year 2006/07. During the JAS period of the same years the calculated contri-
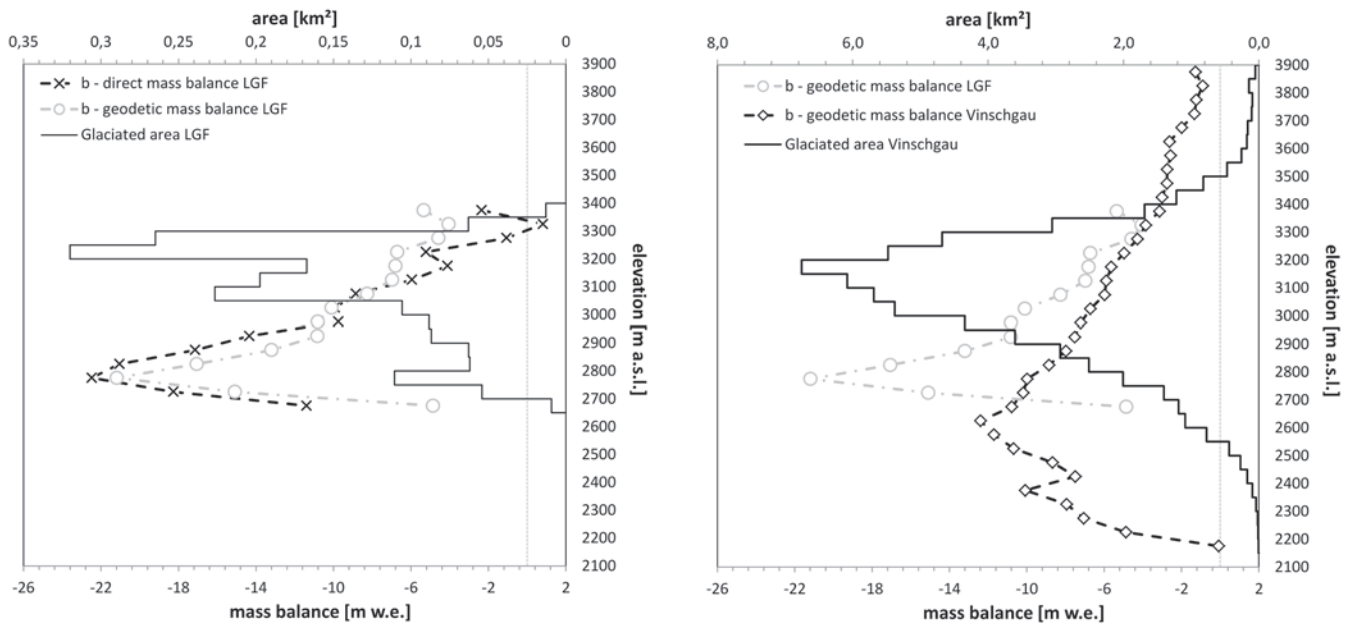
FIG. 7 - Altitudinal distribution of surface area 2005 and specific mass balance for the period fall 2005 to fall 2013 at LGF (left panel). Altitudinal area distribution of all studied glaciers and altitudinal distribution of ALS derived specific mass balance for the study region and LGF (right panel).

bution rates amount to 2.1 % and 26.1 % respectively (tab. 1). The maximum contribution in 2006/07 can be explained by the coincidence of an exceptionally dry winter resulting in low seasonal snow cover storage and hence very negative glacier mass balances. Consequently, the runoff from melting snow cover during early summer was lacking while the excess discharge due to glacier melt was high resulting in a large relative contribution of the latter to total runoff. In contrast, the minimum in 2012/13 is due to a relative large amount of snow related seasonal water storage released during summer and only slightly negative glacier mass balances.

CONCLUSION AND OUTLOOK

We have presented the first results of an interdisciplinary project carried out at the University of Innsbruck which aims to investigate the contribution of glacier melt to total river discharge in the Vinschgau / Val Venosta. We quantified changes in area, volume and mass for 92 glaciers and glacierets in the study region based on very accurate high resolution multi-temporal ALS data from fall 2005 and fall 2013. Results reveal drastic mass loss and areal shrinkage on all glaciers in the study region and a widespread decrease in

TABLE 1 - Key numbers related to the calculation of annual amounts of regional glacier mass change and the resulting contribution to total river discharge in the Etsch / Adige at the village of Töll / Tel. Directly measured annual mass balance at LGF (b LGF), relative fraction of annual to total mass loss at LGF (b LGF relative), regional glacier mass loss (GML reg), annual runoff at Töll / Tel (RO Töll), runoff at Töll / Tel during July to September (RO Töll JAS), as well as glacier melt contribution to total annual runoff (GMC) and to runoff during July to September (GMC JAS) at Töll / Tel.

Year	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	Total
b LGF [kg/m²]	-1456	-1616	-1637	-998	-659	-1078	-1532	-221	-9197
b LGF relative [%]	15,8	17,6	17,8	10,9	7,2	11,7	16,7	2,4	100,0
GML reg [10⁹ kg]	61	68	69	42	28	45	65	9	388
RO Töll [10⁹ kg]	875	761	1111	1192	1049	1094	1060	1242	8386
RO Töll JAS [10⁹ kg]	323	261	504	433	440	403	369	434	3168
GMC [%]	7,0	9,0	6,2	3,5	2,6	4,2	6,1	0,8	4,6
GMC JAS [%]	19,0	26,1	13,7	9,7	6,3	11,3	17,5	2,1	12,2

surface elevation even in the highest glaciated areas of the study region.

The series of directly measured mass balance at LGF for the period 2003/04 to 2013/14 were analyzed in terms of regional representativeness of both, the inter-annual variability, as well as the magnitude of the measured mass balances. A comparison of the directly measured balance series at LGF to data of eight other measured glaciers in the Eastern Alps yields a satisfying representation of the annual signal. The geodetic mass balance of LGF was compared to those of all other individual glaciers showing that LGF is amongst the glaciers with the highest rates of mass loss in the region during the period 2005 to 2013. Despite the sufficient results, the analyses also show the need for further investigations within follow-up studies related to the mass balance record of LGF.

A cross check of the mass balance derived from direct measurements with the geodetic mass balance at LGF yields minor differences between the two approaches revealing that a calibration of the directly measured values is not required.

A simplified approach was applied in order to provide a first order estimate of the annual contribution of glacier retreat to total river discharge in the study region. Results show that the mean annual excess discharge within the period fall 2005 to fall 2013 amounts to about 4.6 % with a minimum value of less than 1 % in the hydrological year 2012/13 and a maximum of 9 % in 2006/07. Values for the period July to September are in the order of 12 % and vary between 2.1 % in 2013 and 26.1 % in 2007. Although the simplified approach applied is most probably subject to larger errors, it was shown that the current seasonal contribution potential of excess discharge due to glacier retreat can reach more than 25 % of the total river discharge and hence requires more detailed investigation in future studies.

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