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Exceptional thinning through the entire altitudinal range of Mont-Blanc glaciers during the 2021/22 mass balance year

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Abstract

Widespread glacier losses have been observed in most glaciated regions on Earth during recent decades, with a typical pattern of strong thinning in their lower reaches and limited elevation changes in their accumulation areas. Here, we use Pléiades satellite stereo-images of the Mont-Blanc massif (Alps) to reveal that thinning took place through the entire elevation range during the exceptional 2021/22 mass-balance year. Above 3000 m a.s.l. on Argentière glacier and Mer de Glace, thinning rates exceeded 3.5 m a^{-1} while almost no change occurred during the previous 9 years. Below 3000 m a.s.l., these anomalous thinning rates are essentially explained by changes in surface mass balance. At higher altitudes, other processes such as firn densification may play a role. Our analysis shows that high altitude glaciers, mostly stable during the last 100 years, are now responding to the impact of climate change.

1. Introduction

The impact of the climatologically-extreme mass-balance year 2021/22 (defined from 1st October 2021 to 30 September 2022) on Central European glaciers has been widely reported in the media (e.g., https://climate.copernicus.eu/esotc/2022/land-cryosphere) and has also been the topic of a few recent studies (Cremona and others, 2023; Six and others, 2023; Voordendag and others, 2023). The exceptionally negative mass balances resulted from below average winter accumulation followed by an exceptionally long and strong melt season (Six and others, 2023). However, these earlier studies did not examine changes over the highest reaches of Central European glaciers (> 3500 m a.s.l.), so the altitudinal extent of ice loss is yet to be fully established. We used here the digital elevation model (DEM) differencing method (Berthier and others, 2023) to document the influence of this exceptional year on the surface elevation of glaciers in the Mont-Blanc massif. We derived DEMs from Pléiades stereo-pairs acquired in 2012, 2021 and 2022 to observe the 9-yr and 1-yr glacier elevation changes and report on the altitudinal distribution of the exceptional thinning rates during the 2021/22 mass-balance year. We put emphasis on the well-surveyed Argentière and Mer de Glace glaciers and also on the Bossons Glacier, flowing from the Mont-Blanc summit.

2. Data and methods

The agility of the Pléiades 1A (launched December 2011) and 1B (launched December 2012) optical satellites allows the acquisition of stereo-pairs with a 0.7 m resolution. We generated 4-m DEMs from five Pléiades stereo-pairs using the semi-global matching algorithm of the Ames Stereo Pipeline (Beyer and others, 2018) and the set of parameters from Deschamps-Berger and others (2020). Pléiades images are coded over 12 bits (4096 grey levels), compared to 8 bits only for older sensors such as ASTER. This ensures almost no saturation in snow-covered areas, strongly reducing the fraction of gaps in the DEMs (Berthier and others, 2023). We coregistered the DEMs on stable terrain, masking out glacierized areas using a glacier inventory from year 2015 (Paul and others, 2020). We next corrected spatially-coherent biases in the elevation difference maps using a polynomial fit across-track and a spline fit in the along-track direction (Falaschi and others, 2023). We filled data gaps using the local hypsometric method to compute glacier-wide elevation changes (McNabb and others, 2019).

We calculated uncertainties at the 95% confidence level on the mean elevation change over a given area (an altitude band or an entire glacier) using the patch method (Miles and others, 2018, their Fig. 2b). This method assesses, using stable terrain, the relationship between the uncertainty on the mean elevation change and the averaging area, using patches varying here from 0.01 to 20 km^2.

We derived our main results from three Pléiades stereo-pairs acquired at almost the same time of the year (19 August 2012, 15 August 2021 and 8 August 2022), which avoids the need for seasonal corrections (Appendix Table A2). Each of these three acquisitions provided DEM coverage across >90% glacier area. We used Pléiades DEMs from 12 October 2021 and 5 October 2022, also almost one-year apart, to confirm the 2021/22 elevation changes derived from the August images, albeit with more data gaps.

We evaluated Pléiades-derived elevation changes using in situ global navigation satellite systems (GNSS) centimetric measurements performed during the first half of September each year along four profiles on the Mer de Glace and four on Argentière glaciers (Fig. 1b). For the mass-balance year 2021/22, the mean difference of the profile-averaged elevation changes was 0.26 m for the August DEMs (Std dev. 0.37 m, $n = 8$) and 0.12 m for the October DEMs (Std dev. 0.41 m, $n = 8$). These differences exhibit a nonsignificant positive bias with altitude of 0.25 m every 1000 m (similar for both August and October elevation changes) suggesting that the satellite data may slightly underestimate thinning rates at high elevation.

We interpreted our results using surface mass balance (SMB) measurements made seasonally on these two glaciers since September 1993 by the GLACIOCLIM observatory. We processed these in situ observations using the nonlinear mass balance model, a statistical model specifically designed to work with sporadic mass balance data spread across a large elevation range (Vincent and others, 2018).

3. Results

The elevation differences measured between 15 August 2021 and 8 August 2022 show glacier thinning of sufficient magnitude and extent to be able to distinguish glaciers from the elevation change grid without the aid of glacier outlines (Fig. 1a). This is symptomatic of thinning which affected the entire elevation range of these glaciers. When compared to the thinning rates from 19 August 2012 to 15 August 2021, the 2021/22 values are rather similar on the lower tongues of the Mer de Glace and Argentière glaciers, below 2100 m a.s.l. (Figs 1c, 1d and 2), possibly due to the lack of an updated glacier inventory or the influence of debris cover on ablation. Above this altitude, the thinning rates are strongly enhanced in 2021/22, reaching 3 to 4 m a^{-1} over most of the glaciers, up to their highest elevations. The glacier-wide elevation change rates between 2021 and 2022 were -3.41 ± 0.26 m a^{-1} (90% coverage), -3.91 ± 0.25 m a^{-1} (90%), -2.84 ± 0.29 m a^{-1} (79%) on Argentière, Mer de Glace and Bossons glaciers respectively. This is, respectively, 5.0, 5.4 and 15.0 times as negative as the rate of elevation changes for 2012–21 (-0.63 ± 0.11 m a^{-1}, -0.78 ± 0.10 m a^{-1}, -0.19 ± 0.14 m a^{-1}).

The map of elevation changes derived from Pléiades stereo-images acquired 12 October 2021 and 5 October 2022 (Figs 1c–e and 2) confirms our August results albeit with a 2-month shift in time. The glacier-wide elevation change rates were -3.28 ± 0.40 m a^{-1} (72% coverage), -3.83 ± 0.33 m a^{-1} (76%), -1.92 ± 0.44 m a^{-1} (61%) on the Argentière, Mer de Glace and Bossons glaciers, respectively.

4. Discussion

4.1. Uncertainties in DEM differencing

Agreements between the satellite-derived August and October 2021/22 elevation changes and the GNSS annual measurements confirm the < 0.5 m uncertainty for Pléiades DEM differencing inferred from the stable terrain and obtained in other studies (Rieg and others, 2018; Błaszczyk and others, 2019; Wagnon and others, 2021). On Bossons Glacier only, the difference between the August and October 2021/22 glacier-wide elevation changes lies outside error bars with stronger thinning rates derived from the August DEMs (-2.84 ± 0.29 m a^{-1}) than from the October DEMs (-1.92 ± 0.44 m a^{-1}) and differences increasing with altitude above 3200 m a.s.l. (Fig. 1e). Four factors can contribute to these differences. First, the 12 October 2021 DEM exhibits some large data gaps above 4000 m a.s.l. due to clouds (Appendix Fig. A3). Second, the October 2021/22 elevation difference dataset is affected by some undulations (amplitude up to 3 m) due to Pléiades-1B satellite jitter during the acquisition of the 12 October 2021 stereo-pair (Appendix Fig. A3). Such along-tracks undulations are common in Pléiades satellite DEMs (Deschamps-Berger and others, 2020; Beraud and others, 2023) and are corrected here by fitting a spline to a mean profile of elevation difference in the North–South (along-track) direction. However, our correction is poorly-constrained at the latitude of Bossons Glacier because of the lack of stable terrain. The August 2021/22 elevation difference exhibits minor along-track biases (amplitude of 0.4 m or less, Appendix Fig. A3). Third, the off-glacier pixels above 4000 m a.s.l. suggest that there could be a slight negative bias in the August 2021/22 elevation change dataset. However, this negative bias is poorly constrained as the ice-free terrain is scarce and the terrain slopes are high, increasing the elevation change uncertainty. Further, the melting of small off-glacier snow patches during the 2022 exceptional heatwave could also contribute to this negative bias. Fourth and finally, more September and October high elevation snowfalls occurred in 2022 than 2021 and could have contributed to the differences between the August and October results.

4.2. Interpretation based on SMB anomalies

Annual elevation change maps do not provide direct insights into the processes that drove these exceptional thinning rates. Point-based glaciological measurements can help to determine how anomalous SMB conditions contributed to this exceptional thinning.

We analyse both types of annual measurements (geodetic and glaciological) as temporal anomalies compared to the reference period, 2012–2021 (Table 1). This 9-year reference period is chosen to match the availability of the Pléiades-derived elevation change map. We focus the analysis on seven sites (P4, P5, P7 and Cirque on Argentière Glacier ; TRE, TAC, Midi on Mer de Glace, Fig. 1) where we have the highest confidence in the SMB measurements.

On Argentière Glacier (4 sites) and in the ablation area of the Mer de Glace (profiles TRE and TAC), the SMB anomalies almost entirely explain the anomalies in the rates of elevation change. The remaining differences (referred to as ‘residuals’), always less than 0.4 m a^{-1} and of varying signs, may result from uncertainties in the measurements, slightly different temporal and spatial sampling for the SMB and GNSS campaigns and anomalies in vertical velocities (section 4.3).

Our highest site (‘Midi’ for Mer de Glace) is at an altitude (3500 m a.s.l.) where the SMB was positive over the last 20 years and close to 0 during 2021/22. The SMB-derived elevation change anomaly is -2.13 ± 0.55 m a^{-1}, i.e. 0.65 ± 0.74 m a^{-1} less negative than the observed elevation change anomaly (-2.78 ± 0.50 m a^{-1}), albeit with large associated uncertainty. Thus, SMB changes may not fully explain the excess thinning at high elevations.

Overall, SMB anomalies show that strongly enhanced ablation occurred during 2021/22 at least up to 3500 m a.s.l. (our highest measurement site), and that these anomalies explain most of the excess thinning below this altitude. However, we lack SMB measurements above 3500 m a.s.l. to assess confidently if other processes (discussed below) contributed to part of the thinning at the uppermost elevations, up to 4800 m a.s.l.

4.3. Uncertain (but likely minor) contribution of vertical velocities

The mass balance year 2021/22 was exceptional, with larger than usual water input to the subglacial hydrological network. Hence,

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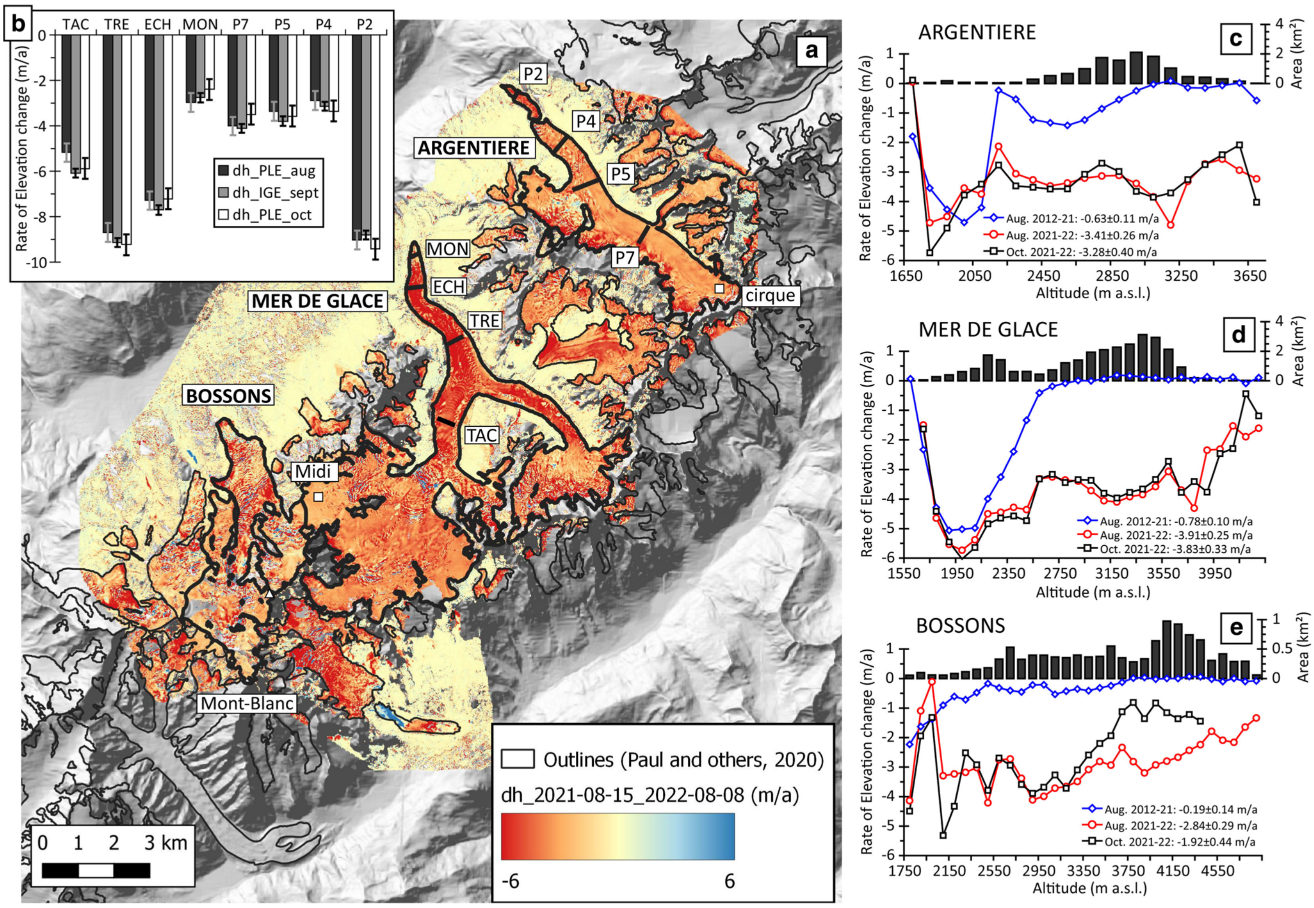

Figure 1. (a) Rate of elevation differences (m a^{-1}) over the Mont-Blanc massif between 15 August 2021 and 8 August 2022. Slightly thicker glacier outlines are used to distinguish the three main glaciers, Argentière, Mer de Glace and Bossons from North to South. GNSS profiles are marked by eight straight, black lines across Mer de glace and Argentière glaciers, with white squares representing two key mass balance sites (Cirque and Midi). (b) Comparison of profile-averaged elevation changes during mass-balance year 2021/22 derived from Pléiades August stereo-pairs (dh_PLE_aug, black), September GNSS measurements (dh_IGE_sept, grey) and Pléiades October stereo-pairs (dh_PLE_oct, white). The three right panels compare, for Argentière (c), Mer de Glace (d) and Bossons (e) glaciers, the annual rate of elevation change with altitude for three periods, August 2012 to August 2021 (blue), August 2021 to August 2022 (red) and October 2021 to October 2022 (black). Glacier-wide mean values are provided in the legend. The upper black histograms represent the hypsometry. Reduced thinning rates at the glacier fronts are due to the lack of ice to melt following rapid glacier retreat. .

one may expect some anomalies both in horizontal and vertical glacier velocities (Clarke, 2005; Flowers, 2015), that could contribute to the anomalous thinning.

However, in the ablation areas of both Mer de Glace and Argentière glaciers, repeated GNSS measurements of stakes suggest only modest velocity anomalies during 2021/22, except at the TAC profile on Mer de Glace where a 10% increase in horizontal velocity was measured. A possibility is that spring and early summer speed up events were compensated by slowdown in late summer, when the subglacial network is well-developed (Nanni

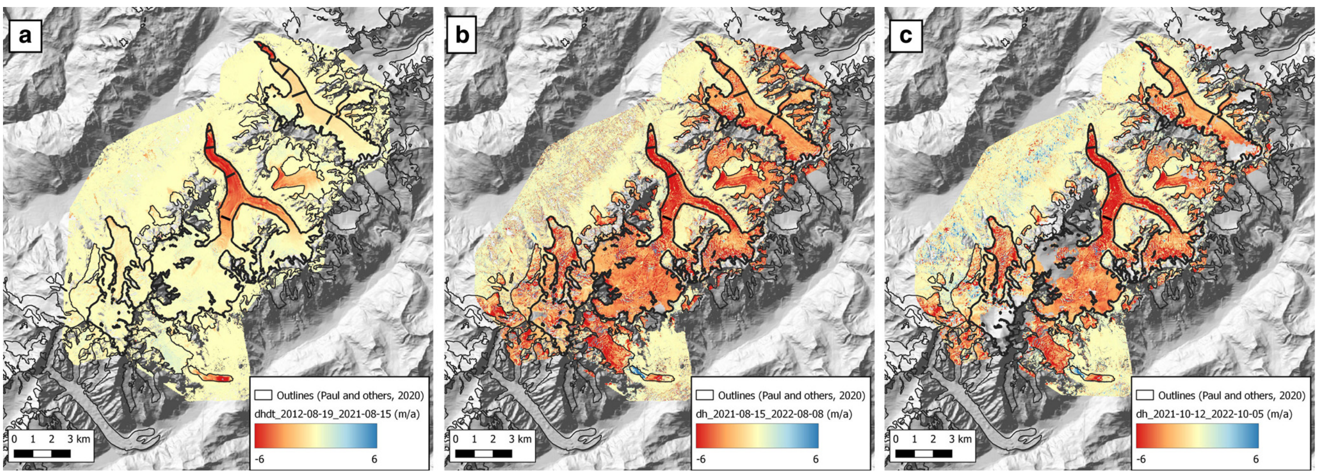

Figure 2. Rate of elevation changes (m a^{-1}) over the Mont-Blanc massif between 19 August 2012 and 15 August 2021 (a), 15 August 2021 and 8 August 2022 (b) and 12 October 2021 and 5 October 2022 (c).

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Table 1. Temporal anomalies in SMB (in m water equivalent (w.e.) a^{-1}) and elevation change rates for the mass balance year 2021/22 compared to the 2012–21 reference period at four sites on Argentière Glacier and 3 sites on the Mer de Glace

Glacier	Site	Elevation (m a.s.l.)	SMB anomaly (m w.e. a^{-1})	Density (kg m^{-3})[a]	Elevation change rate anomaly computed from SMB anomaly (m a^{-1})	GNSS elevation change rate anomaly (m a^{-1})[b]
ARG	P4	2380	−2.39 ± 0.30	900 ± 15	−2.65 ± 0.34	−3.03 ± 0.20
	P5	2540	−2.11 ± 0.30	900 ± 15	−2.34 ± 0.34	−2.20 ± 0.20
	P7	2715	−2.29 ± 0.30	900 ± 15	−2.54 ± 0.34	−2.59 ± 0.20
	Cirque	2960	−2.20 ± 0.30	600 ± 60	−3.67 ± 0.51	−3.57 ± 0.50[c]
MDG	TRE	1980	−1.80 ± 0.30	900 ± 15	−2.00 ± 0.33	−1.60 ± 0.20
	TAC	2170	−1.77 ± 0.30	900 ± 15	−1.97 ± 0.33	−2.36 ± 0.20
	Midi	3500	−1.17 ± 0.30	550 ± 55	−2.13 ± 0.55	−2.78 ± 0.50[c]

SMB anomalies are converted to elevation change rate anomalies using average densities measured during field campaigns. Sites are located in Fig. 1.
[a]Uncertainties in the densities are taken from Thibert and others (2008).
[b]Uncertainties in the GNSS elevation changes are taken from Vincent and others (2009).
[c]At these two sites (Cirque and Midi), repeat GNSS measurements are not measured and were replaced by elevation change rates derived from August Pléiades elevation models.

and others, 2023). On a multi-year scale, at sites P5 and P7 on Argentière Glacier, a steady and small trend of 0.07 m a^{-2} of vertical velocities has been observed between 2006 and 2018 (Fig. 11 in Vincent and others, 2021) and can also explain part of the residuals in Table 1.

In the accumulation area, vertical velocity is influenced by changes in glacier dynamics (sliding and internal deformation) and by firn densification rate of the layers below the last summer horizon. These two factors are examined:

(1) There are no measurements at sites Cirque and Midi to detect any anomaly in vertical velocity during the year 2021/22. Above 3800 m a.s.l., as glaciers are cold-based (Gilbert and others, 2014), no sliding is expected and rapid changes in velocity are thus unlikely. However, such rapid changes could occur between 3000 and 3800 m a.s.l. Seasonal satellite-derived surface velocity fields could help to fill this knowledge gap in the future.
(2) At altitudes where the firn is cold, i.e. mostly above an altitude of 3500 m a.s.l. but with variations depending on glacier dynamics, excess meltwater will refreeze in the firn and not reach the bed. We speculate that a fraction of the very high elevation excess thinning during the year 2021/22 could be due to enhanced densification of the firn layers older than one year. A possibility is that unusual melt events during the June, July and August 2022 heatwaves (Guinaldo and others, 2023) resulted in firn densification rates higher than usual (Ochwat and others, 2021), contributing to the exceptional thinning rates at very high altitude. Unfortunately, we lack repeat measurements of the vertical firn density profiles after the 2021/22 mass balance year to support this hypothesis. We note that a densification of only 3.3% of the upper 20 m firn column at the site Midi, i.e. a mean density increasing from 600 kg m^{-3} (Jourdain and others, 2023) to 620 kg m^{-3}, would be sufficient to induce the fraction of the excess thinning (0.64 m a^{-1}, Table 1) unexplained by the SMB anomaly.

5. Conclusions

Using high resolution Pléiades satellite stereo-imagery, we observed the exceptional thinning of Mont-Blanc glaciers during the glaciological year 2021/22. Below 3000 m a.s.l., ice thinning is essentially explained by a strong negative anomaly in SMB. Above 3000 m a.s.l., thinning reached 3–4 m in a single year, values 5–15 times larger than average rates during the previous nine years. SMB anomalies likely drove a large fraction of this high elevation thinning during 2021/22 but there are no SMB measurements above 3500 m a.s.l. to confirm it. Excess thinning due to anomalous ice flow velocities is likely small but also poorly constrained. We speculate that densification of the deep cold firn layers may have contributed to the excess thinning at high elevations but we lack repeat density profiles to quantify this component of glacier elevation change.

From 1905 to 2005, the elevations at the summit of Mont-Blanc (4810 m a.s.l.) or nearby Dôme du Gouter (4300 m a.s.l.) did not change by more than 3 m (Vincent and others, 2007). Our measurements of thinning rates of about 3 m in the accumulation areas up to the highest elevations for the mass balance year 2021/22 suggest that Mont-Blanc glaciers may have entered a new regime in which their upper reaches are now also impacted by climate change.

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Authors' contributions. EB designed the study, processed the satellite data and led the writing. CV & DS collected and processed the field measurements, contributed to the discussion of the results and to the writing.

Data availability. The grids of elevation changes derived from August and October Pléiades DEMs for the 2012–2021 and 2021–2022 periods are available here: https://zenodo.org/record/8047784. In situ SMB and GNSS data for Argentière and Mer de Glace are available on the GLACIOCLIM web site https://glacioclim.osug.fr.

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Appendix

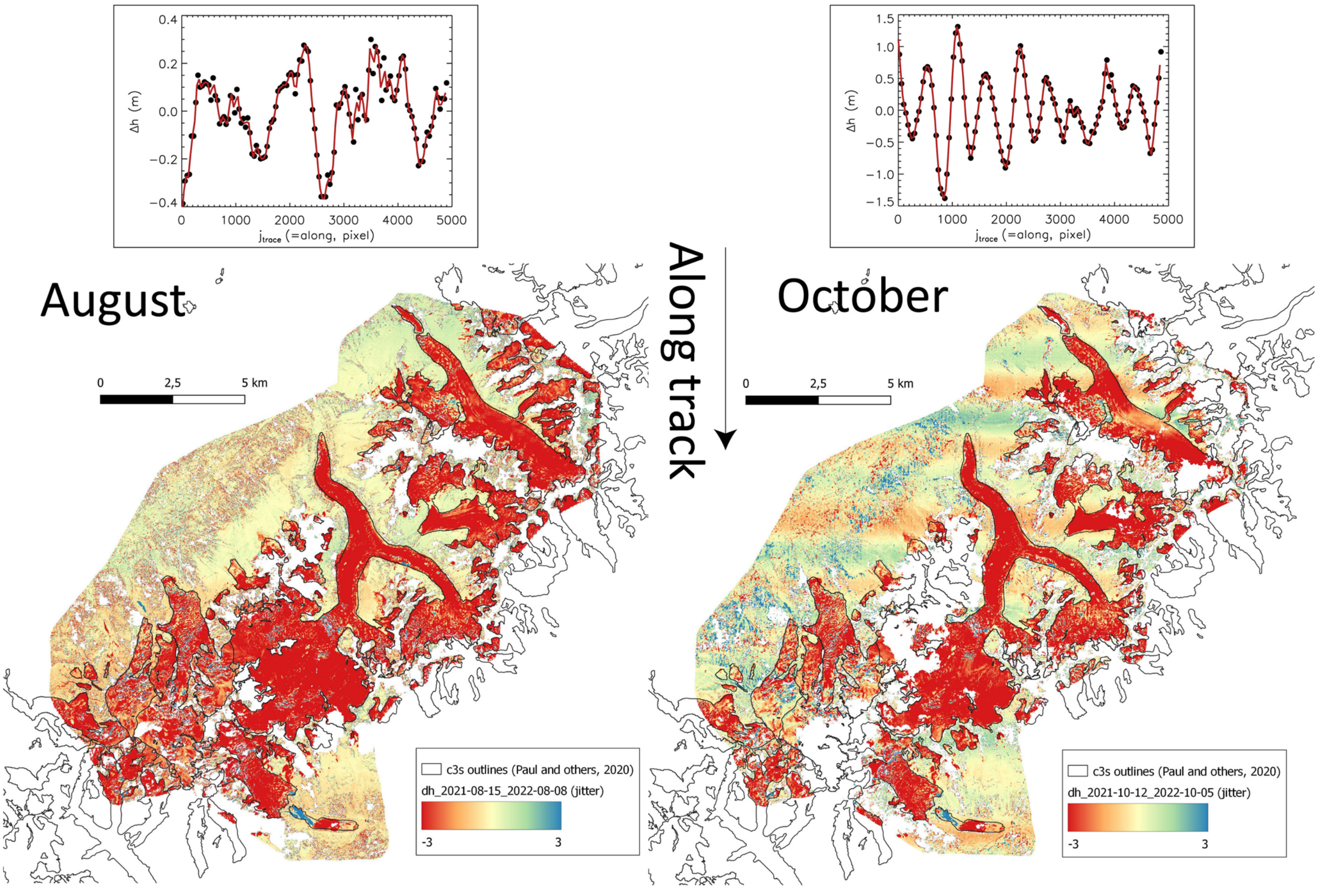

Figure A3. 2021/22 elevation differences (m) derived from the August (left panels) and October (right panels) Pléiades DEMs before the along and across track bias corrections. The upper panels show the average profiles of elevation differences in the North to South direction, with, as a continuous red line, a spline fit to the original data (note the different *Y*-axis). The colour scale of the maps is different than in Figs 1, 2 to magnify the off-glacier elevation differences.

Table A2. List of Pléiades stereo-images used in this study

Date	Image Id in the Airbus DS catalogue	Base-to-height ratio
2012-08-19	DS_PHR1A_201208191041325_FR1_PX_E006N45_1222_02484	0.33
2021-08-15	DS_PHR1A_202108151037206_FR1_PX_E006N45_1222_01712	0.60
2021-10-12	DS_PHR1B_202110121041200_FR1_PX_E006N45_1222_01712	0.56
2022-08-08	DS_PHR1B_202208081033134_FR1_PX_E006N45_1221_02258	0.48
2022-10-05	DS_PHR1A_202210051037158_FR1_PX_E006N45_1222_01712	0.64

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