Multi-temporal elevation changes of Fedchenko Glacier (Tajikistan) from 1928 to 2021

Journal:	*Journal of Glaciology*
Manuscript ID	Draft
Manuscript Type:	Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Brun, Fanny; Institut des Geosciences de l'Environnement, IRD Lambrecht, Astrid; Bavarian Academy of Sciences and Humanities, Geodesy and Glaciology Mayer, Christoph; Bavarian Academy of Sciences and Humanities, Geodesy and Glaciology Rezaei, Janali; Institut des Geosciences de l'Environnement, IRD Dehecq, Amaury; IGE, Beraud, Luc; Institut des Géosciences de l'Environnement, Deschamps-Berger, César; Pyrenean Institute of Ecology-CSIC, Jaca, Spain Berthier, Etienne; Université de Toulouse, LEGOS (CNES/CNRS/IRD/UT3) Voelksen, Christof; Bavarian Academy of Sciences and Humanities, Geodesy and Glaciology KAYUMOV, Abdulkhamid; Center for Research of Glaciers of the National Academy of Sciences of the Tajikistan
Keywords:	Glacier mass balance, Glacier surges, Laser altimetry, Mountain glaciers
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	co-registration. The 93-year mean rate of elevation change is -0.46 m yr-1. Notably, the tongue's thinning rate is twice as negative as the long-term average in two sub-periods (1958-1980 and 2010-2021), possibly linked to a surge-like event for the earlier period. Analyses of ERA5 reanalysis (1950-2021) and Fedchenko meteorological station data (1936-1991) reveal a dry anomaly in 1958-1980 followed by a wet anomaly in 1980-2010, potentially offsetting temperature-induced mass losses. The contemporary thinning rates align with a broader trend of generalised mass losses in the Pamir region.

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Fanny BRUN,[1] Astrid LAMBRECHT,[2] Christoph MAYER,[2] Janali REZAEI,[1] Amaury DEHECQ,[1] Luc BERAUD,[1] César DESCHAMPS-BERGER,[3] Etienne BERTHIER,[4] Christof VÖLKSEN [2], and Abdulkhamid KAYUMOV[5]

[1] *Univ. Grenoble Alpes, IRD, CNRS, INRAE, Grenoble INP, IGE, 38000 Grenoble, France*

[2] *Bavarian Academy of Sciences and Humanities, Munich, Germany*

[3] *Pyrenean Institute of Ecology-CSIC, Jaca, Spain*

[4] *Université de Toulouse, LEGOS (CNES/CNRS/IRD/UT3), Toulouse, France*

[5] *Center for Research of Glaciers of the National Academy of Sciences of the Tajikistan*

Correspondence: Fanny Brun <fanny.brun@univ-grenoble-alpes.fr>

ABSTRACT. The Fedchenko Glacier in Tajikistan's central Pamir region is one of Asia's longest glacier and has been a focal point for scientific investigation spanning the 20th and 21st centuries, yielding a valuable historical dataset for Central Asia. This study explores elevation changes from 1928 to 2021 from topographic maps from 1928 and 1958, KH-9 spy satellite data from 1980, SPOT5 satellite data from 2011, and Pléiades satellite data from 2017, 2019, and 2021, along with GNSS surveys for absolute co-registration. The 93-year mean rate of elevation change is -0.46 m yr^{-1}. Notably, the tongue's thinning rate is twice as negative as the long-term average in two sub-periods (1958-1980 and 2010-2021), possibly linked to a surge-like event for the earlier period. Analyses of ERA5 reanalysis (1950-2021) and Fedchenko meteorological station data (1936-1991) reveal a dry anomaly in 1958-1980 followed by a wet anomaly in 1980-2010, potentially offsetting temperature-induced mass losses. The contemporary thinning rates align with a broader trend of generalised mass losses in the Pamir region.

INTRODUCTION

Due to heavy irrigation and high domestic water demand in the Amu Darya basin, the Pamir mountains play a crucial role for downstream freshwater supply (Immerzeel and others, 2020). The Amu Darya basin contains more than 10,000 km^2 of glaciers, that provide around 5.5 $\pm$ 1.9 Gt of meltwater every year (Pritchard, 2019; Miles and others, 2021). Glaciers lost less mass in this region in the beginning of the twenty-first century, compared both with high mountain Asia and global averages (Gardelle and others, 2013; Lin and others, 2017; Brun and others, 2017; Shean and others, 2020; Hugonnet and others, 2021).

There is a large temporal gap in ground-based glacier monitoring in Central Asia following the collapse of the Union of Soviet Socialist Republics (USSR). Most scientific activities in this region were abandoned in the 1990s, with some of them being re-established in the past years (Hoelzle and others, 2017). This gap is being partially filled in the north-western Pamir (Pamir Alay) by the re-interpretation of firn cores and profiles collected in the 1970s, combined with modelling of glacier mass balance (Barandun and others, 2015; Kronenberg and others, 2021, 2022). In the eastern Pamir, the mass balance of Muztag Ata No. 15 Glacier was reconstructed from 1980 to 2017 (Zhu and others, 2018; Bhattacharya and others, 2021). In the Tien Shan mountains of Kyrgyzstan, a comparison of historical and recent firn cores established a reconstruction of the surface mass balance in the accumulation area of Grigoriev ice cap (Machguth and others, 2024). All these studies found a tendency to increased accumulation on glaciers during the last 40 to 60 years together with an increased melt, that explain relatively stable mass balance in the region (Zhu and others, 2018; Kronenberg and others, 2021; Machguth and others, 2024).

Still, in the western Pamir data remain scarse. Scientific activities focused on the longest mountain glacier in the region: Fedchenko Glacier (now called Vanjyakh; 660 km^2, approx. 69 km long from Jasgulem pass to the front), located in Tajikistan. The long-term mass balance of the glacier was calculated for the period 1928-2000 (Lambrecht and others, 2014) and 1975-1999 (Zhou and others, 2019). However, these studies are limited by the lack of high quality topographic data in the upper part of the glacier area, that are hampered by penetration issues for the X and C-band radar data (Rignot and others, 2001; Dehecq and others, 2016; Lambrecht and others, 2018) and by saturation issues for the optical data, leading to incomplete coverage. GNSS data partially compensate these disadvantages, thanks to their high precision, but they are not acquired frequently and provide only a partial coverage, being thus difficult to compare to raster data.

In this study, we re-visit topographic data from 1928 and 1958 acquired by the Russian-German expedition of 1928 and by the Academy of Sciences of the Uzbek Republic expedition of 1958 (Lambrecht and others, 2014, and references therein). We combine these data with a digital elevation model (DEM) derived from KH-9 imagery from August 1980, a SPOT5 DEM from November 2011, Pléiades DEMs acquired in fall 2017, summer and fall 2019, and fall 2021, ICESat data from fall 2003 and GNSS data from August 2009, 2015, 2016 and 2019. The series of glacier elevation change is then analyzed in light of temperature and precipitation changes from weather station data and reanalysis products (ERA5).

STUDY AREA

Fedchenko Glacier is one of the longest glacier in Asia, with a centerline longer than 75 km (RGI Consortium, 2023). It is located in the central Pamir in Tajikistan. Its is fed by different accumulation basins, whereof the largest one is located at the head of the main trunk, above 4 800 m a.s.l (Lambrecht and others, 2014). Jasgulem pass (5 300 m a.s.l.) separates the main accumulation areas of Fedchenko and Jasgulem glaciers (Fig. 1). Fedchenko Gacier has multiple tributaries glaciers of various sizes, with Bivachny Glacier being one of the most remarkable (Fig. 1) that is known for its past surges (Wendt and others, 2017).

DATA AND METHODS

Elevation Data

Historical maps

Historical maps of Fedchenko Glacier were produced by two expeditions in 1928 and 1958 (Finsterwalder and others, 1932; Dittrich, 1964; Lambrecht and others, 2014) by terrestrial photogrammetry at a scale of 1:50 000. The maps are all based on the same local geodetic system, defined by astronomic measurements during the expedition in 1928. Scans of the original maps have been orthorectified according to their original projection. Then, the elevation contours and glacier boundaries have been digitised and interpolated on a regular grid with a resolution of 20 m by 20 m. The errors of the final gridded elevation models are estimated to less than 35 m in location and about 10 m in elevation (Lambrecht and others, 2014). Further details about the map coverages and DEM generation can be found in Lambrecht and others (2014).

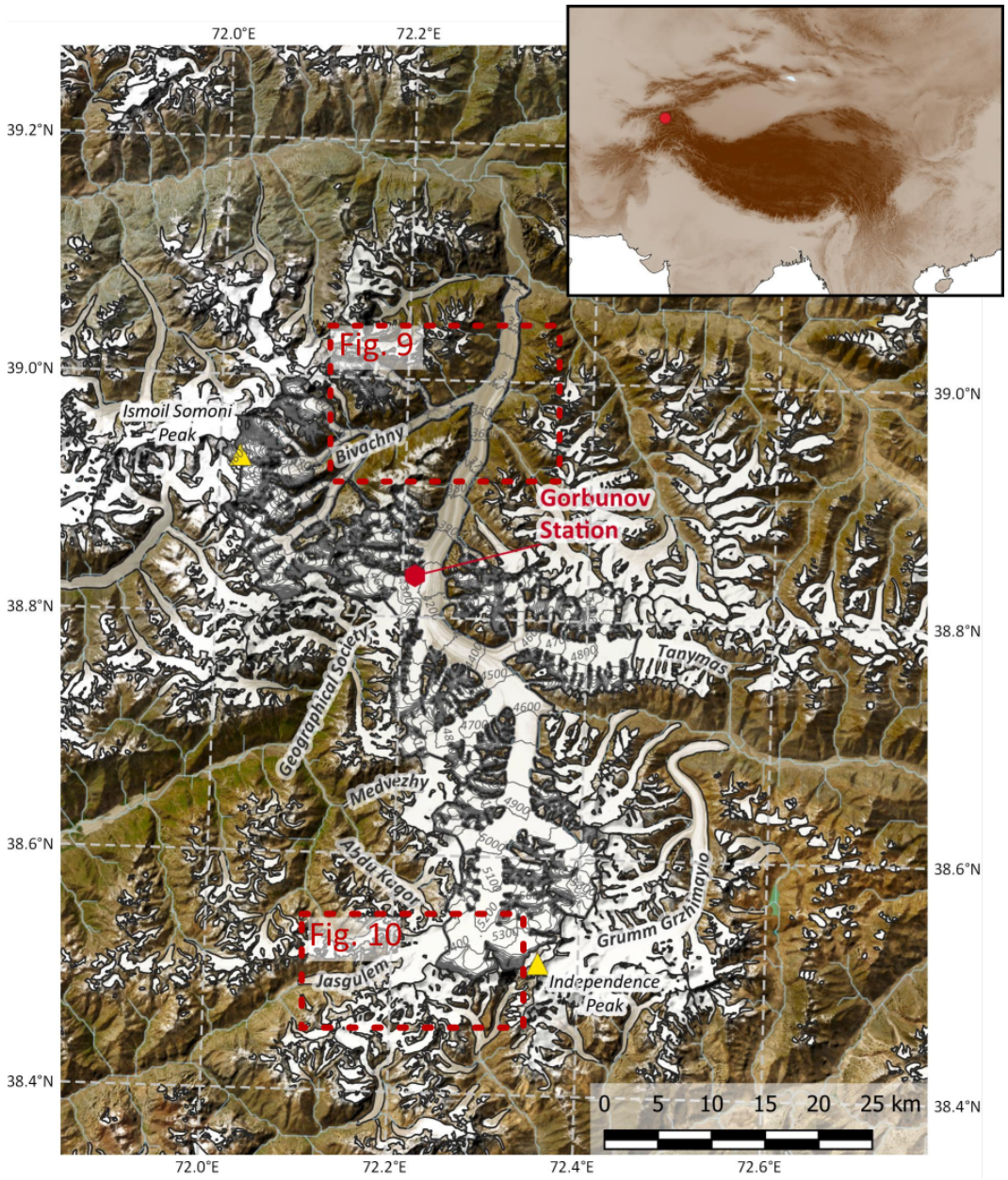

Fig. 1. Map of Fedchenko Glacier and surrounding area. The red dot on the inset map shows the location of Fedchenko Glacier. Some of the large neighbouring glaciers are named on the map. The location of Gorbunov meteorological station is highlighted, as well as the confluence with Bivachny Glacier and Jasgulem pass that are also shown of figures 9 and 10. Background image is the ESRI satellite product.

Table 1. Summary of gridded elevation data used in this study

Date of acquisition	Sensor/ Instrument	Fedchenko area covered (percent)	Vertical precision (one sigma) (m)	Comments/source
1928	Historical map	76	10	Lambrecht and others (2014)
1958	Historical map	40	10	Lambrecht and others (2014)
20 Aug. 1980	KH9	89	5	Dehecq and others (2020)
19 Nov. 2011	SPOT5	62	5	Gardelle and others (2013)
15 Oct.–23 Nov. 2017	Pléiades	73	1	Long time span
1–2 Aug. 2019	Pléiades	34	1	Upper glacier area only
28–29 Aug. 2019	Pléiades	41	1	Upper glacier area only
22–23 Sept. 2019	Pléiades	41	1	Upper glacier area only
20 Sept. 2021	Pléiades	53	1	

Digital elevation models from optical satellite images

In this study, we use DEMs from different types of optical images, that were all processed without ground control points (Table 1). All the elevation data are posted in the UTM 43N coordinate system and the elevations are provided relative to the WGS84 ellipsoid.

A pair of declassified KH-9 Hexagon images acquired on 20 August 1980 over the Pamir region was selected. This image pair is different from the image of 13 July 1975 used by Zhou and others (2019). We chose the image of 1980 because it was acquired closer to the end of the ablation season, and hence was more favourable to study glacier elevation changes. Additionally, the images from 1980 are less saturated in the accumulation basin of Fedchenko Glacier, leading to the reconstruction of a larger area compared to the images of 1975. The images were processed following Dehecq and others (2020).

Also, the SPOT 5 HRS DEM from Gardelle and others (2013) was included in the study. This DEM was produced by the French Mapping Agency (IGN) using correlation parameters defined during the SPIRIT (SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies) International Polar Year project (Korona and others, 2009). We used the DEM derived with the second set of parameters (v2), that is in principle better suited for mountainous terrain (Korona and others, 2009; Gardelle and others, 2013). Pixels with a correlation score below 75 were excluded, leading to large data voids in the accumulation area (Fig. A1). Finally, we converted the elevation provided with the Earth Gravitational Model 1996 geoid

(EGM96) as reference to the WGS84 ellipsoid using the *dem_geoid* command of NASA's Ames Stereo Pipelines (ASP, Beyer and others, 2018).

In addition, we use five Pléiades DEMs from 2017, 2019 and 2021 (Table 1). The acquisitions of 2019 are restricted to the upper basin, and the acquisition of 2017 does not cover the lowermost section of the tongue (Fig. A1). Apart from the images of early August 2019, the images are not saturated thanks to the 12 bit encoding and the specific acquisition parameters (Berthier and others, 2024). The pairs of images were processed using ASP. We used a semi global matching algorithm, which proved appropriate for snow covered areas (Deschamps-Berger and others, 2020). Each Pléiades DEM in Table 1 was obtained by stitching up to three DEMs corresponding to the respective individual Pléiades pairs that did not cover the whole glacier area. In 2019, for a given date, all the scenes were acquired within two days, ensuring very limited terrain changes, even over glacierized area. In 2017, the different scenes were acquired more than one month apart (15 October to 23 November). However, due to the cold period and the limited snowfall between the different acquisitions, we assume that changes in elevation are likely minor even on the glacierized area. Thus stitching was done by co-registering the different DEMs of 2017 using a Nuth and Kääb (2011) co-registration algorithm that considers the entire area covered by the DEMs (and not only the off glacier terrain).

ICESat data

Over the whole ICESat record, there is only one track that intersected Fedchenko Glacier in fall 2003 (Fig. A2). ICESat footprints from the Geoscientific LASer instrument (GLAS) were converted from the EGM2008 geoid to the WGS84 ellipsoid using the NSIDC GLAS Altimetry elevation extractor Tool (NGAT). The nominal precision of ICESat is estimated around 0.1 m (Zwally and others, 2002). We averaged the elevation of the Pléiades 2021 DEM in disks of 70 m diameter around the ICESat footprint center-point and excluded the footprints with a standard deviation of elevation larger than 2 m that corresponds to slopes steeper than approximately 10 degrees. After filtering, we kept 63 footprints that were all acquired on 7 October 2003 (Table 2 and Fig. A2).

GNSS data

GNSS data were gathered during the summers of 2009, 2016, and 2019, employing various GNSS systems. Initially, only GPS and GLONASS were utilized, but with the advancement of Galileo, it was integrated

Table 2. Summary of point scale data used in this study

Date of acquisition	Sensor/Instrument	Number of points	Comments
7 Oct. 2003	ICESat	63	
18–29 Aug. 2009	GNSS	9038	
7–22 Aug. 2016	GNSS	329994	
4–17 Aug. 2019	GNSS	160883	16586 points excluded

into the 2019 campaign. All measurements were conducted using multi-frequency systems to optimize GNSS signal utilization. The antenna was mounted on a sledge, maintaining a constant height above the surface. In 2009, the analysis relied on a local GNSS reference station on the glacier, whose coordinates were estimated using data from the nearest International GNSS Service (IGS) site. The sledge's coordinates were then computed relative to this local reference station. After 2009, Precise Point Positioning (PPP) became the method for position estimation, relying on precise clock and orbit data from GNSS satellites. This approach eliminates the need for a local reference station, simplifies fieldwork as there is no setup or maintenance required for power supply.

The accuracy of each position is better than 10 cm in the horizontal component and 20 cm in height, which is still a conservative estimate (Lambrecht and others, 2018). Coordinates were determined within the International Terrestrial Reference Frame (ITRF). In the first two campaigns, coordinates were referenced to ITRF2008, while the last campaign used the ITRF2014, introduced shortly before. Both reference frames exhibit negligible differences with a typical magnitude of 1 cm, which can be regarded as it is well within other source of uncertainties. The current realisations of WGS84 and various ITRFs also differ slightly in the centimetre range, as they have different originators. However, for our practical purposes, we consider them to be identical and will summarize both under the term WGS84 in the following chapters.

Elevation change methods

Co-registration

All the elevation data (i.e. GNSS and DEMs) are converted to the same spatial reference system (WGS84) and projected into UTM coordinates (43N) using ellipsoidal heights. For the DEMs derived from historical maps of 1928 and 1958, Lambrecht and others (2014) ensured the consistency between the original astronomical system and the WGS84 ellipsoidal elevation, which includes correcting the map elevations by a

32 m offset. This offset agrees well with the geoid height provided by the EGM96. Details regarding the processing of the maps are available in Lambrecht and others (2014) and in references therein. The location error was estimated around 35 m, and due to the limited stable terrain available, we did not apply another co-registration strategy (Lambrecht and others, 2014). The DEMs from optical satellite data, calculated from orbital parameters, are not perfectly georeferenced. For each of them, the horizontal and vertical georeferencing can have an offset of up to dozen of meters. As a consequence, the DEMs need to be tied to the GNSS data and co-registered to each other before being differentiated.

We first co-registered the 1-2 August 2019 Pléiades DEM on the GNSS data acquired on 4 to 17 August 2019. Due to the insufficient variety of slope and aspect, automatic algorithms did not perform well. Instead, we manually found the horizontal displacement (x and y direction) that minimized the typical aspect dependent pattern of horizontally shifted elevation products (Berthier and others, 2007; Nuth and Kääb, 2011). The standard deviation of the difference between the Pléiades DEM and the GNSS points is 0.41 m after excluding one spurious series of GNSS measurements (Fig. A3). We then co-registered each Pléiades DEM (of 2017, 2019 and 2021) on the mosaic of 1-2 August 2019 DEM using a classical co-registration algorithm (Nuth and Kääb, 2011). The 2021 Pléiades DEM covers a larger terrain, and is used as a reference to co-register all the remaining DEMs that were not derived from Pléiades images.

Analyzing spatially discontinuous elevation changes

One of the challenges of studying the elevation changes of a glacier that has the size of Fedchenko glacier is the difficulty to obtain precise elevation data that cover the whole glacier area. In particular the GNSS measurements were acquired along individual profiles, and even if there are some cross overs between profiles in the different years, they provide only localized elevation changes. In order to combine elevation information from different spatial sampling, we apply a method inspired from ICESat processing (Kääb and others, 2012). We create a 700 m wide buffer along the glacier centerline, which we split into 1 km long sections along the main glacier flow, these sections are called patches hereafter (Fig. 4). We differentiate all the available elevation data (DEM and GNSS) with regard to the Pléiades 2021 DEM. GNSS data are differentiated with the Pléiades 2021 DEM using the *Point sampling tool* in QGIS. ICESat data are differentiated with the average elevation of the Pléiades 2021 DEM in disks of 70 m diameter around the footprint center-point.

For each patch and for each year i, we calculate the average elevation change relative to the 2021

DEM for each period ($\overline{dh_{i-2021}}$). For the discrete measurements (ICESat and GNSS) we do not apply any filtering. For the continuous measurements (DEMs) we consider as valid the patches with more than 40% of data coverage. For each sub-period between the years i and j, we calculate the elevation change ($\overline{dh_{i-j}}$) as:

$$\overline{dh_{i-j}} = \overline{dh_{i-2021}} - \overline{dh_{j-2021}} \quad (1)$$

using 2021 as the general reference level.

Uncertainties on elevation changes

Uncertainties on elevation changes are very difficult to quantify due to the heterogeneous sources of data and the spatial averaging done here. The main sources of uncertainties on elevation changes are: i- the intrinsic precision of the data, ii- the spatial sampling and iii- the temporal sampling.

Intrinsic precision of the data

Due to the limited stable terrain and the contrast between the rugged stable terrain and gentle glacier terrain, we cannot apply standard methods to evaluate the spatial structure of variance (e.g., Rolstad and others, 2009; Hugonnet and others, 2022). Instead, we report only one single metrics of DEM precision, which are based on the literature (Table 1). We do not account for the effect of spatial averaging for DEM differences because we investigate patches that are expected to be small with respect to the decorrelation length of the DEM differences. At the scale of the patch, the errors are thus highly correlated. However, when looking at a collection of patches, the spatial correlation reduces due to the distance between patches.

Spatial sampling

For the point-scale measurements (GNSS and ICESat), we need to test whether the measured elevation changes are representative of the patch they belong to. To assess the impact of the spatial sampling, we sampled the Pléiades 2017 and 2021 DEMs at the locations of each GNSS point and ICESat footprint. For each patch, we average the elevation differences obtained with the GNSS or ICESat sampling, and compare it with the 2017-2021 DEM difference averaged over the same patch. We find that the GNSS sampling is very representative for both campaigns, with a mean difference of 0.00 m (std of 0.28 m) for the 2009 GNSS campaign and 0.05 m (std of 0.34 m) for the 2016 GNSS campaign. For ICEsat, we find lower accuracy with a mean difference of -0.17 m and a standard deviation of 0.54 m. The difference is

likely due to the fact that the ICESat track intersects the side of the glacier, while the GNSS tracks follow the centerline (Fig; A2).

Temporal sampling - Seasonal correction of the GNSS elevations

The GNSS data were acquired around mid-August (Table 2). These dates are not ideal to calculate elevation changes, which should preferentially be calculated between matching dates at the end of the ablation season (i.e. 1 October). The sub-annual acquisitions of Pléiades data in 1-2 August, 28-29 August and 22-23 September 2019 were used to derive a correction (in m) that was applied to the GNSS data of 2009 and 2016 (Fig. A4). The correction is calculated as the difference between the end of September DEM minus the average of the two-August DEMs, which is a proxy for a mid-August DEM. This seasonal correction is available only for the upper part of the glacier, above 4500 m. It averages at -0.66 m, can be as negative as -1.53 m, and has generally a higher magnitude for lower elevations, with the exception of the highest locations that experienced a thinning of 0.90 m over the end of summer 2019.

We applied the seasonal correction to GNSS data only, because the ICESat data were acquired very close to the target date of 1 October (Table 2). Regarding the DEMs, only one was acquired more than one month before the end of the ablation season (the KH9 DEM of 20 Aug. 1980), but we did not apply a correction as it would have a small impact on yearly change rates due to the long time spans considered.

Meteorological data

Meteorological data originate from two sources: the Gorbunov/Fedchenko Station (Williams and Konovalov, 2008) located at 4169 m on the eastern side of the glacier and ERA5 reanalysis data (Hersbach and others, 2020). We use monthly values of temperature and precipitation from both sources. We also use monthly snowfall from ERA5 reanalysis data, in order to discriminate solid and liquid precipitation. Fedchenko Station operated from 1936 to 1994, providing an exceptional climate record in this data scarce and remote area. ERA5 reanalysis was recently extended back to 1950, which lead to an overlap of 44 years between the two records. We collected ERA5 series of temperature, precipitation and snowfall from the closest grid point to the station (72.25, 38.75). It has a geopotential height of 44368 m^2 s^{-2}, corresponding to an elevation of 4527 m, assuming $g_0 = 9.80$ m s^{-2}.

Meteorological methods

Bias correction in ERA5 data

Due to the height difference between the station and ERA5 grid point and the cold bias in mountainous area in ERA5 (e.g., Orsolini and others, 2019; Khadka and others, 2022), we find a temperature bias of -5.9 K in ERA5, relative to the Gorbunov station. After correcting for this bias, we still observe a season dependent bias, with the spring/summer months being positively biased up to 1.6 K in April, and the fall/winter months being negatively biased down to -2.3 K in November (Fig. A5). After removing a monthly bias, the final match between ERA5 monthly temperature and the station monthly temperature is very good, with a bias equal to zero, and an RMSE at 1.4 K (Fig. 2a). At annual scales, the agreement between ERA5 and the station is also satisfying (Fig. 3). For the shared period, the inter annual variability is slightly higher in ERA5 (0.66 K) than in the station data (0.53 K).

There is more dispersion in the difference between ERA5 and the station records for precipitation than for temperature, with a systematic underestimation of precipitation in ERA5. We multiply the ERA5 precipitation by 1.9, which minimize both the RMSE and the bias between the two series (Fig. 2b). The comparison shows a RMSE of 38 mm in the monthly precipitation data, but the bias between the two series is limited, with a mean bias of 1 mm, which ensures that the two series can still be merged (Fig. 3). Note that these statistics are calculated excluding the station data after 1990, because there is a systematic negative bias in the precipitation records (Fig. A6). For the shared period, the station has a higher inter-annual variability (std of 305 mm yr^{-1}) than ERA5 (std of 175 mm yr^{-1}). We apply the same factor of 1.9 to correct ERA5 snowfall.

Temperature and precipitation anomalies

We create two meteorological records named “ERA5 priority” and “station priority”, depending on which dataset is used in the shared period. For the reconstructed temperature and precipitation series, the anomalies are calculated on a monthly basis for the whole period (1936 until 2020). For each year, we calculate the anomaly in each variable by subtracting the monthly averages over the whole period to the monthly series. We also calculate annual snowfall anomalies from ERA5 record. Note that the latter are calculated as percentage, and are thus unaffected by the precipitation correction factor.

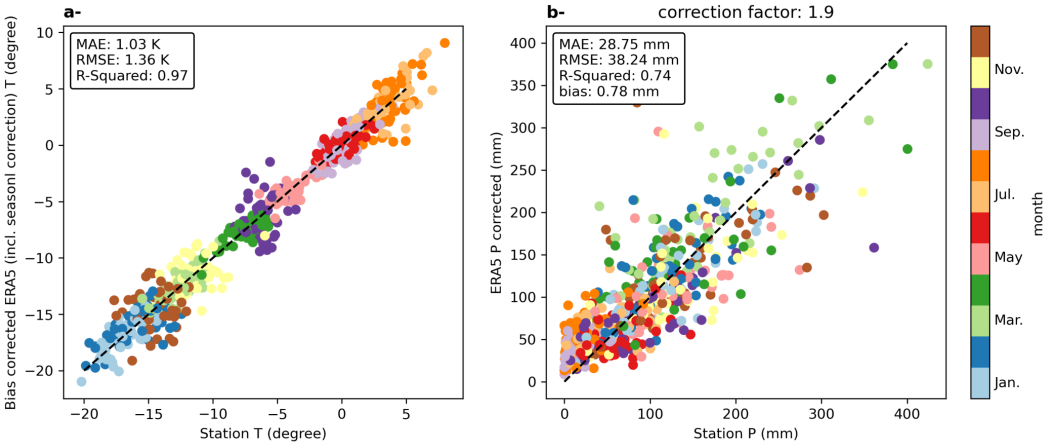

Fig. 2. Comparison of the monthly ERA5 bias corrected temperature (a) and precipitation (b) with the monthly station record for the overlapping years (1950-1994). Note that the years 1990 to 1994 were excluded for the precipitation data, due to spurious values in the station record.

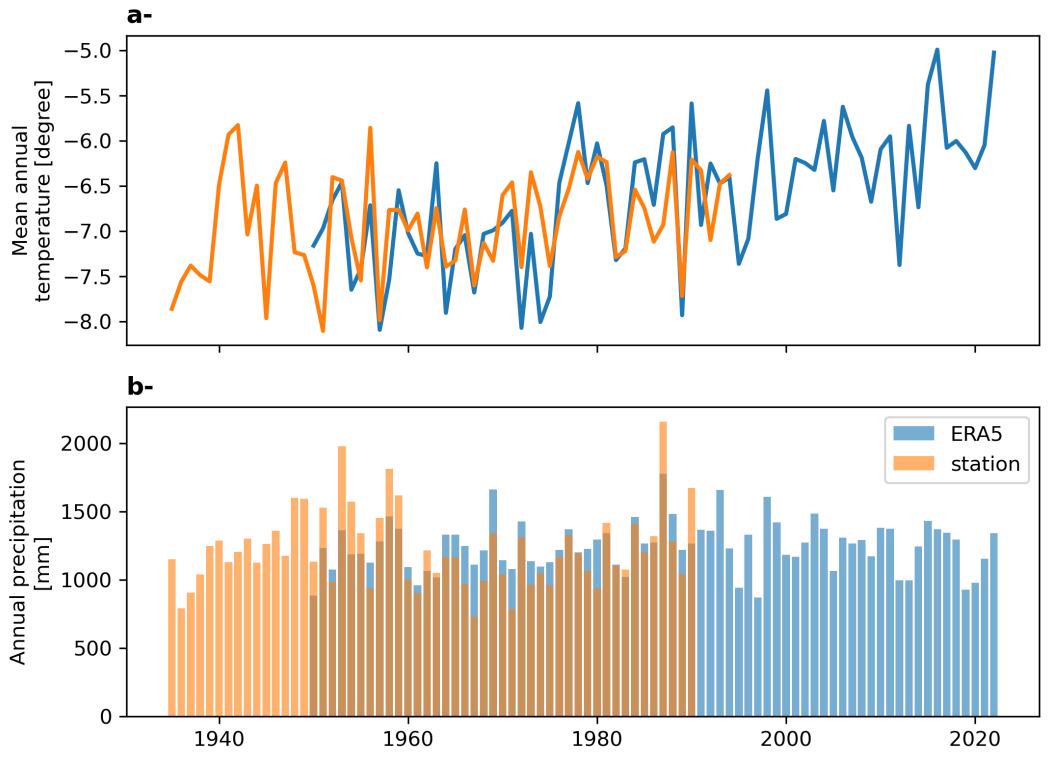

Fig. 3. Series of annual temperature (a) and precipitation (b) from ERA5 corrected and from the station record

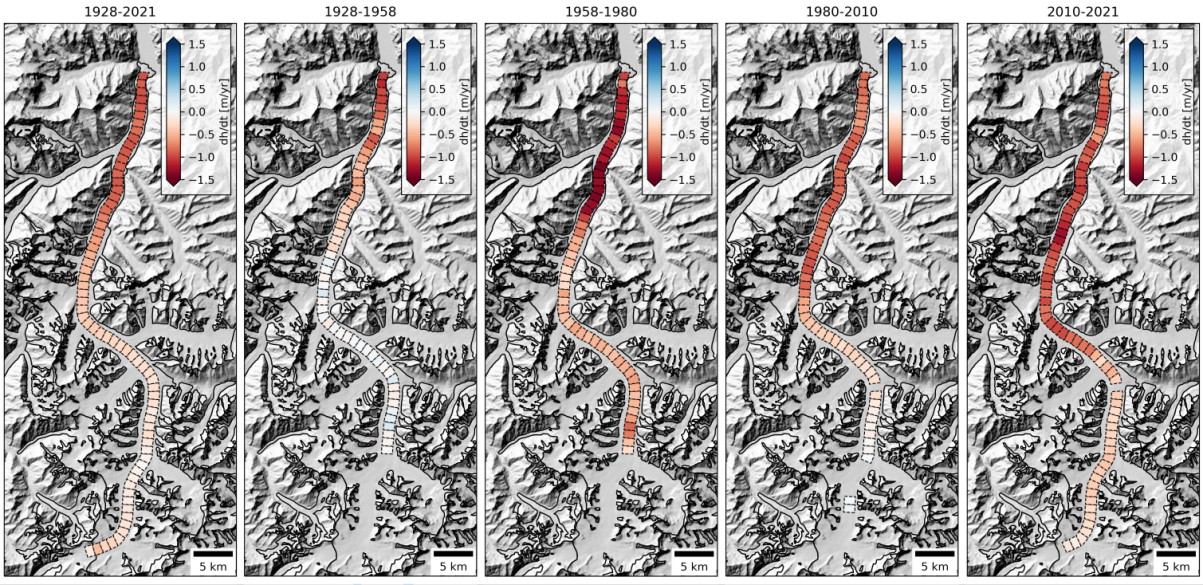

Fig. 4. Rates of elevation changes along the main trunk of Fedchenko Glacier for the different sub-periods. Background is a hillshade from the Copernicus 30 m DEM (GLO-30DEM; European Space Agency, 2022).

RESULTS

Multi-decadal elevation changes

For the period 1928-2021, the coverage of the glacier with elevation information is high (Table 1), especially along the central flowline that is fully covered. We observe a mean thinning rate of 0.46 m yr^{-1}, with a maximum thinning of 89.4 m (corresponding to 0.96 m yr^{-1}) roughly 4 km from the glacier front around 3100 m a.s.l. (Fig. 4 and Table 3). The thinning is relatively homogeneous for the lower reaches and then decreases with elevation from approximately 80 m at 3700 m a.s.l, to less than 10 m at 4600 m a.s.l. There is almost no elevation change detectable from 4600 to 5000 m a.s.l. (dh/dt around -0.10 m yr^{-1}; Fig. 4 and 5), but thinning increases again above 5000 m a.s.l. reaching approximately 30 m at Jasgulem pass (5250 m a.s.l.).

For the four sub-periods (1928-1958, 1958-1980, 1980-2010 and 2010-2021), the coverage is not always complete. For the period 1928-1958, we limit the analysis to the area below 4900 m a.s.l., because of spurious data above this elevation (Lambrecht and others, 2014). During this 30-year period, thinning is moderate in the tongue region (-0.31 m yr^{-1}) and close to zero for most of the surveyed area located between 3700 and 4900 m a.s.l. For the period 1958-1980, we observe a marked thinning at all elevations, with a maximum thinning of -1.44 m yr^{-1} around the confluence with Bivachny Glacier. The pattern of

Table 3. Rate of elevation changes for the different sub-periods. The shared area corresponds to locations that are sampled during all sub-periods, and is thus restricted to lower reaches of the glacier. The upper area corresponds to elevations above 4 600 m a.s.l. and the lower area corresponds to elevations below 4 600 m a.s.l.. For some periods the upper area is very poorly sampled and the mean elevation change is not very meaningful, these values are marked with a star (*).

Period	1928-2021	1928-1958	1958-1980	1980-2010	2010-2021
Mean dh/dt [m yr^{-1}] - whole area	-0.46	-0.27	-0.76	-0.56	-0.69
Mean dh/dt [m yr^{-1}] - shared area	-0.55	-0.27	-0.77	-0.59	-0.79
Max. dh/dt [m yr^{-1}] - shared area	-0.96	-1.12	-1.44	-1.01	-1.26
Mean dh/dt [m yr^{-1}] - lower area	-0.61	-0.31	-0.80	-0.68	-0.87
Mean dh/dt [m yr^{-1}] - upper area	-0.18	0.02*	-0.54*	-0.07*	-0.31

elevation change is peculiar, as there is a rather sharp transition towards less negative rates of elevation changes seven kilometers upstream of the confluence with Bivachny Glacier. Significant thinning rates are still observed at all elevations, until the maximum observed elevation of 4900 m a.s.l. For the period 1980-2010, the glacier thinned in the lower parts (-0.68 m yr^{-1}), but slightly thickened in the main trunk from 4700 to 5200 m a.s.l. It is noteworthy that the year 2010 reconstruction is a combination of the SPOT5 DEM of November 2011, for elevations below 4600 m a.s.l. and of the GNSS measurements of August 2009 for the upper parts (Figs. A1 and A2). For the period 2010-2021, the thinning is observed at all altitudes, with rates of elevation change around -0.87 m yr^{-1} for the tongue, and a homogeneous elevation change rate of -0.31 m yr^{-1} in the whole accumulation area (Fig. 4).

In order to compare the different sub-periods in a more quantitative way, we calculate the mean rate of elevation change over the area covered in all the sub-periods (see "shared area" in Table 3). We find an elevation change rate of -0.55 m yr^{-1} for the period 1928-2021. The period with the most limited changes is 1928-1958, with a rate of -0.27 m yr^{-1}, while the period 1980-2010 is close to the long term average with -0.59 m yr^{-1}. The two sub-periods 1958-1980 and 2010-2021 are the most negative ones with rates of elevation changes of -0.77 and -0.79 m yr^{-1}, respectively.

If we compare the most recent period (2010-2021) with the earlier 82 years (1928-2010), the most striking feature is the up-glacier propagation of substantial thinning rates (> 1 m yr^{-1}) at elevations above 3700 m a.s.l. (Fig. 5). In contrast, the thinning rates of the lowest parts of the glacier are very similar and average at -0.90 m yr^{-1} below 3600 m a.s.l. for both periods. We find opposite results at the upper most

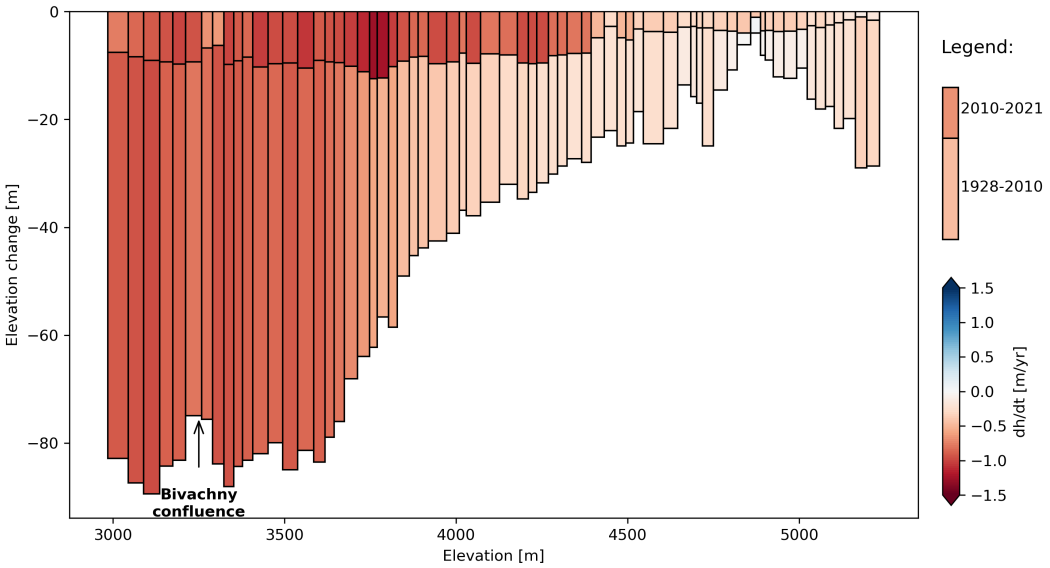

Fig. 5. Elevation changes for the periods 1928-2010 and 2010-2021 for different elevations along the centerline of Fedchenko Glacier. The bar length represents the elevation change and their color the rate of elevation change. The bar width represents the altitudinal span of each patch. The arrow shows the location of the confluence with Bivachny Glacier, and the reduced thinning due to the surge of Bivachny (Wendt and others, 2017).

elevations (above 5200 m a.s.l. at Jasgulem pass), where the early thinning rate of -0.32 m yr^{-1} is larger than the contemporary one at -0.13 m yr^{-1}.

2003-2021 elevation changes

Short term elevation changes are available only for the accumulation basin, and are based largely on ICESat, GNSS data, and Pléiades DEMs (Fig. 6). The 2003-2009 period coverage is limited, because it is based on a single ICESat track from 7 October 2003, despite a good coverage from the GNSS in 2009 (Fig. A2). It is also noteworthy that ICESat sampling represents less accurately the spatial variability (see method section). Still, we observe significant thinning, ranging from -0.57 to -0.28 m yr^{-1} in the upper accumulation basin from 2003 to 2009. This period is followed by a period (2009-2016) of more moderate thinning, that averages at -0.21 m yr^{-1}. The last period (2016-2021) is the most spatially contrasted, with areas of strong thinning (-0.82 m yr^{-1}) and areas of thickening up to 0.16 m yr^{-1} (Fig. 6).

It is difficult to compare the three sub-periods, because of the limited spatial coverage for the period 2003-2009. However, the mean rate of elevation change is roughly twice as negative for the period 2016-2021, than for the period 2009-2016, with mean rates of elevation changes of -0.41 and -0.21 m yr^{-1},

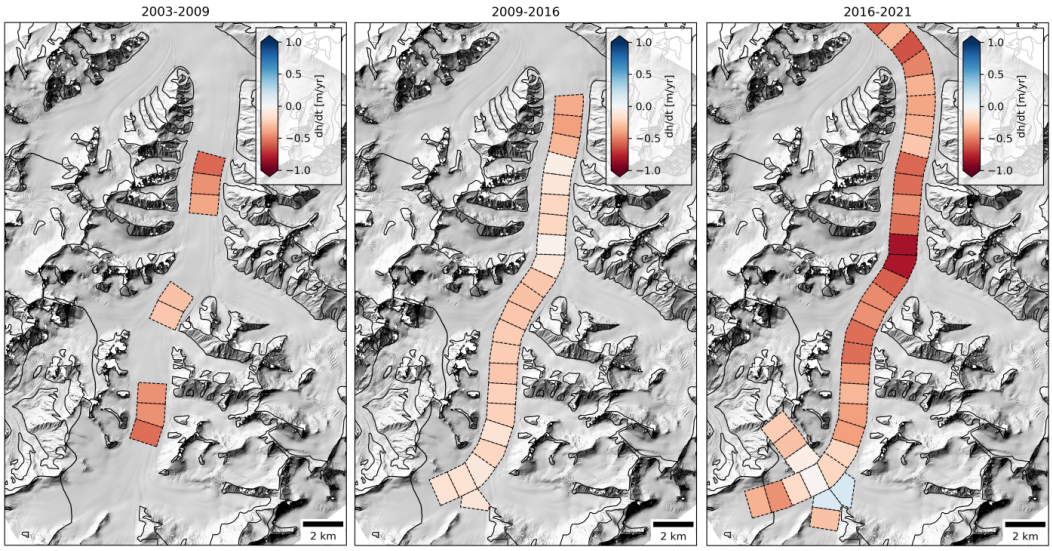

Fig. 6. Rates of elevation changes for three sub-periods in the higher part of Fedchenko Glacier from 2003 to 2021.

respectively. The thickening pattern for the period 2016-2019 is a robust pattern, also visible in the 2015 GNSS data (not shown here, because the coverage is scarce). There is little dependency of the elevation change with elevation. For instance, the maximum thinning rate for the period 2016-2021 is located at 4900 m a.s.l. For the period 2009-2016 the rate of elevation change is slightly higher for the lower elevations, but differences are still rather small.

Overall, the accumulation basin of Fedchenko Glacier has thinned at a substantial rate since 2000, but it is difficult to quantify the magnitude of these changes and their acceleration. The recent rates of elevation changes (2010-2021) are more negative than the long term trend (1928-2010), with the exception of Jasgulem pass, where most of the changes happened before 2010.

Meteorological changes

Both reconstructed time series show a continuous increase in temperature (Fig. 7), reaching an annual temperature anomaly of 0.60 K for the period 2010-2021, with respect to the period 1936-2021. Regarding precipitation, the year-to-year variability is large (Fig. 7). In both reconstructed records, there is a positive precipitation anomaly from 1980 to 2010 of 5 to 7 %. Additionally, in the "station priority" record, the period 1958-1980 corresponds to a dry anomaly, with a 10 % precipitation deficit, but this is not visible in the "ERA5 priority" record, which shows only a moderately negative precipitation anomaly for this period (Fig. 7). The snowfall at ERA5 grid point has a marked positive anomaly of 6 % for the period 1980-2010

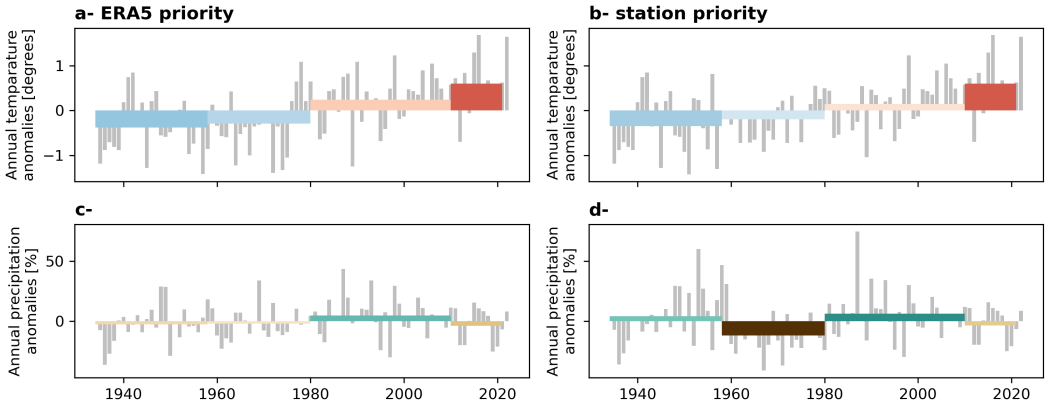

Fig. 7. Anomalies of temperature (a, b) and precipitation (c, d) for the "ERA5 priority" (a, c) and "station priority" (b, d) records. Colored boxes show the period considered in this study bounded by elevation data availability.

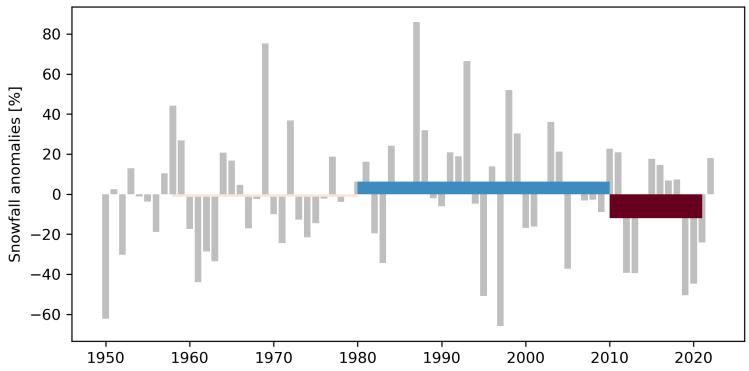

Fig. 8. Annual snowfall anomalies from ERA5 record

and a very negative anomaly of -12 % for the period 2011-2021, which is likely related to the positive temperature anomaly and might not be representative of what happens at higher elevation (Fig. 8).

DISCUSSION

Climate related elevation changes

Long-term elevation changes of Fedchenko Glacier are not homogeneous in time. While it is rather clear that the glacier has been thinning for almost a century (Lambrecht and others, 2014), our study allows to identify different patterns and rates of elevation changes for each sub-period that deciphers a complex glacier/climate relationship.

The earliest period is the one with the most limited changes of the glacier (from the terminus to 4600 m elevation), with an average thinning of -0.27 m yr^{-1} (Table 3). The thinning is still significant, as well as

the tongue retreat, showing that the glacier was already out of equilibrium with climate. The limited data collected above 4 600 m a.s.l show near zero elevation changes, meaning that the surface mass balance was in equilibrium with the dynamics in the upper part of the glacier. This hints towards a slight disequilibrium with climate, that could be an ongoing response of Fedchenko Glacier to the end of the little ice age, which is estimated to culminate around 1600-1650 years AD in the Pamir Alay (Solomina, 2000).

A period of intense thinning between 1958 and 1975 for the glacier tongue was suspected by Zhou and others (2019), because they found lower thinning rates for the period 1975–2000 than Lambrecht and others (2014) for the period 1958–2000. Our study confirms their interpretation, as we find a mean rate of elevation change of -0.77 m yr^{-1} over the shared area for the period 1958-1980. In terms of climatic record, the station data show rather dry conditions (anomaly of -10 %) during this period (Fig. 7), however, this is not reflected in the ERA5 record (Fig. 7). The period 1968–1980 corresponds to negative (-0.52 $\pm$ 0.14 m w.e. a^{-1}) mass balance for Abramov Glacier located in the Pamir Alay, 90 km north of Fedchenko Glacier front (Barandun and others, 2015; Kronenberg and others, 2022), which indicates that mass balance conditions in the region were unfavourable during this time. Thinning in the upper area also suggest dry conditions. Still, the pattern of thinning of the tongue for the period 1958-1980 is difficult to explain by a climatic signal only (see the following discussion section).

The period 1980–2010 corresponds to moderate thinning, and even some slight thickening in the upper area of Fedchenko Glacier (Table 3 and Fig. 4). Moderate glacier mass losses and slight mass gains can be interpreted within the general picture of the "Karakoram anomaly" (Gardelle and others, 2012; Farinotti and others, 2020). This anomaly of positive glacier mass balance is quite well documented for the central Pamir in the beginning of the twenty-first century (Zhu and others, 2018; Lin and others, 2017; Holzer and others, 2015; Brun and others, 2017; Shean and others, 2020), but there is no definitive conclusion about its specific drivers (de Kok and others, 2018; Farinotti and others, 2020). From the ERA5 and station data, it seems that this period corresponds to a wet anomaly (Fig. 7) that led to increased snowfall (Fig. 8). Despite a positive temperature trend and anomaly, the excess precipitation and snowfall might have mitigated the impact of rising temperature, and thus delayed the glaciers' response to this warming. Moreover Fedchenko glacier lies in-between two well studied glaciers Abramov and Muztag Ata glaciers that are sub-continental and continental types of glaciers, respectively. Fedchenko glacier is thus expected to be also of continental/sub-continental type with a relatively low sensitivity to temperature changes (Zhu and others, 2018; Wang and others, 2019; Arndt and Schneider, 2023; Wang and others, 2017).

The last period (2010–2021) is the period of most intense thinning, with a mean elevation change rate of -0.79 m yr^{-1}. This is consistent with the largest positive temperature anomaly, and the slightly negative precipitation anomaly that led to a large snowfall deficit (Fig. 8). The thinning is widespread, including in the upper area of the glacier, where it reaches -0.31 m yr^{-1}, a number in agreement with previous studies (Lambrecht and others, 2018). The most striking feature is the up-glacier propagation of thinning (Fig. 5). It is noteworthy that this 11-yr period is shorter than the other ones, leading to higher uncertainties. The intense thinning is consistent with the accelerating mass losses in high mountain Asia and the possible end of the "Karakoram anomaly" (Hugonnet and others, 2021). The large snowfall anomaly of -12 % for the period 2011-2021 shows that there is also an impact of the rising rain-snow transition, because the snowfall anomaly has a larger amplitude than the precipitation anomaly. The most recent thinning is thus likely a combination of intensified melt and reduced accumulation, due to both a lack of precipitation and reduced proportion of snow fall.

A potential surge on Fedchenko main tongue?

For the period 1958-1980, reduced precipitation should lead to generalised thinning, whereas the most intense thinning happens only at the glacier tongue on the lowest 18 km (Fig. 4). Within two kilometers the rates of thinning changes from -0.8 to -1.3 m yr^{-1}. Such a pattern suggests the implication of ice dynamics as well, and potentially surge related mechanisms. Large thinning rates localised on glacier tongues are frequently interpreted as post surge phases (e.g., Hewitt, 2007; Gardelle and others, 2012), but this criteria is not sufficient to classify a glacier as surge-type. We thus searched for additional evidence to support or to refute this interpretation.

The large thinning is located close to the confluence with the lowest tributary of Fedchenko Glacier, Bivachny Glacier. This tributary is known for its past surges in 1976–78 and 2011–2015 (Kotlyakov and others, 2008; Wendt and others, 2017). The surge of 1976–78 did not reach Fedchenko Glacier (Kotlyakov and others, 2008). To our knowledge there is no documentation about earlier surges, which might have reached Fedchenko main trunk as later surges did, like the 2011–15 surge (Wendt and others, 2017), and impacted the rate of elevation changes on Fedchenko main trunk (Lambrecht and others, 2018). We investigated the field reports from the late 50's but found no evidence of anomalous behaviour of Bivachny Glacier.

We investigated images from the Corona KH-2, KH-4, KH-4B, and Hexagon KH-9 missions that were

acquired over the Pamirs from the sixties, until the eighties (Zhou and others, 2019; Goerlich and others, 2020; Ghuffar and others, 2022, Table 4). The orthoimage of 1968 is from Ghuffar and others (2022), and the orthoimages of 1975 and 1980 are processed according to Dehecq and others (2020). The other images are referenced using stable terrain features identified in the Pléiades orthoimage of 2021 and using the *georeferencer* tool of QGIS. These images are thus not properly orthorectified, but simply registered, leading to large uncertainties on the registration accuracy.

Visual inspection of the images reveals that downstream of the confluence with Bivachny Glacier, the central part of Fedchenko tongue was much more crevassed in December 1960, than in the other years, where it appears covered by debris, with distinct ice cliffs. Additionally, on its right side, Fedchenko Glacier is touching the valley walls in December 1960 whereas the ice is approximately 100 m away from a deposited moraine in August 1968 (Fig. 9). This observation suggests that parts of the thinning happened at the beginning of the 1958-1980 period.

On the historical images, we also find the existence of a looped moraine on Fedchenko main trunk, located close to the confluence with Bivachny Glacier in 1960 (Fig. 9). Looped moraines are common features related to ice flow instabilities (Jennings and Hambrey, 2021). As the looped moraine is preserved over two decades, we could track its location on the historical imagery (Figs. 9 and A7 and Table 4). We assumed an uncertainty of 50 m on the location of the tip of the looped moraine, which is likely a conservative estimate, especially for the most resolved images. The uncertainty in the displacement is thus $\sqrt{2} * 50 = 71$ m, leading to uncertainties on the velocity that range from 12 to 23 m yr^{-1}.

The point scale velocity estimates from this method show that the 1962-1968 velocity is much larger than all the other velocities estimated at this location, with 137 $\pm$ 12 m yr^{-1} versus velocities from 65 $\pm$ 13 to 77 $\pm$ 23 m yr^{-1} for the different periods from 1968 to 1980 (Table 4). The spatial variability of the velocity cannot explain these differences, as the 2017-2018 velocity ranges from 49 to 79 m yr^{-1} at the location of the tip of the looped moraine (Table 4). The looped moraine is located in the vicinity of the historical profile named profile X (Schulz, 1962), where velocity was measured by field techniques from February 1958 until August 1959 (Fig. A7). The mean velocity along profile X for the period 1958-1959 is 26.7 cm d^{-1}, corresponding to 97.5 m yr^{-1} (Schulz, 1962). Given that the looped moraine is located on the side of the glacier, and given the present day observed profile, we can estimate that the velocity at the looped moraine location is approximately 75% of the profile average velocity, which would lead to a velocity of approximately 73 m yr^{-1} in 1958-1959 (Fig. A7. This value is very close to the velocity estimates of the

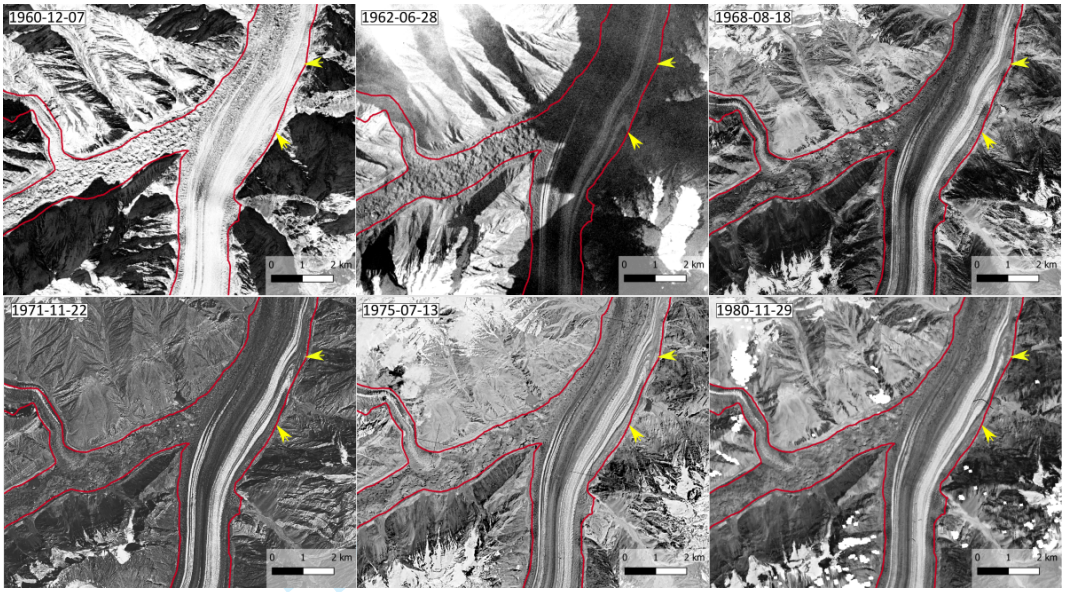

Fig. 9. Temporal evolution of a looped-moraine on Fedchenko main trunk, downstream of the confluence with Bivachny Glacier. Images: KH-4 and KH-9 series (Table 4). The yellow arrows are located at the same place on each image to help locating the looped-moraine and its displacement.

periods after 1968 (Table 4), but this very good agreement is to be taken with some caution, as we do not know exactly how the profile average velocities were measured in 1958-1959 (Schulz, 1962).

The analysis of velocities is still uncertain, but it indicates that the velocity close to the confluence with Bivachny was roughly twice as large between 1962 and 1968, than during all the other periods. We calculated a six year average that hides large temporal variability in velocity, and it is likely that the peak velocity was much larger. It is also noteworthy that this location of Fedchenko Glacier undergoes significant seasonal variability in velocity, with spring velocities being 50 % larger than annual averages, which might complicate the analysis (Nanni and others, 2023).

Given the qualitative and quantitative evidence gathered here, we can conclude that we suspect an internal surge, or at least a large speed-up, of Fedchenko main tongue that happened sometimes between August 1959 and August 1968. The mechanisms that led to this acceleration are completely unclear, but they might be related to pulses of meltwater originating from neighbouring surge-type glaciers. This acceleration did not lead to a front advance, nor to major flow disturbance, explaining why it was not noticed before. The specific surge inventories for the region investigated later periods (Goerlich and others, 2020; Guillet and others, 2022; Guo and others, 2023). Given the extremely high density of surging glaciers in the surroundings, it is not very surprising to observe such kind of glacier flow instability.

Table 4. Additional images used to track the looped-moraine displacement. The values in between two lines represent the displacement of the tip of the looped-moraine and derived velocity between the two consecutive scenes. The present-day velocity is the velocity for 2017-2018 at the tip of the looped-moraine location extracted from Millan and others (2022). Figure A7 shows the locations of the tip of the looped-moraine for the different dates.

Date	Image ID	Mission	Disp. (m)	Velocity (m yr^{-1})	Present-day velocity (m yr^{-1})
1960-12-07	DS009013007DV168	KH-2			
1962-06-28	DS009038031AA024	KH-4			68
			841 ± 71	137 ± 12	
1968-08-18	DS1104-2169DF097	KH-4B			79
			237 ± 71	77 ± 23	
1971-09-21	DS1115-2169DA012	KH-4B			60
			282 ± 71	74 ± 19	
1975-07-13	DZB1210-500134L005001	KH-9			58
			347 ± 71	65 ± 13	
1980-11-29	DZB1216-500273L006001	KH-9			49

The mystery of Jasgulem pass elevation changes

Lambrecht and others (2014) already noticed a substantial thinning of more than 30 m for elevations above ~4700 m a.s.l. for the periods 1928-2000 and 1928-2009. Interestingly, they found that this thinning was increasing with increasing elevation. The data presented in this study show that the 2010-2021 pattern is opposite, with decreasing thinning rates with elevation (Fig. 5). Two previous hypotheses were proposed to explain the thinning: reduced accumulation, due to drier conditions that would lead to an imbalance between discharge and surface mass balance, and/or a densification of the firn due to increased temperature (Lambrecht and others, 2014). The second hypothesis is supported by observations of ice layers in the firn (Lambrecht and others, 2020), but can only partly explain the elevation changes, as the firn densification has a small impact on elevation changes (Ochwat and others, 2021).

The thinning is most pronounced downstream of Jasgulem pass (Fig. 10), an ice divide between ice flow towards Fedchenko Glacier (NE direction; Fig 1) and towards Jasgulem Glacier (SW direction). We report two intriguing features at Jasgulem pass. First, we observe a migration of the topographic divide, approximately 100 m towards Jasgulem between 1928 and 2019 (Fig. 10). The terrain is very flat, leading to high uncertainty on the location of the topographic divide, especially in the 1928 map. The divide

migration does not explain the thinning, but instead we observe that the shape of the elevation profile at the divide location has changed (Fig. 10). In particular, we note that the past divide was more prominent, with slightly steeper slopes within one kilometre in the downstream direction (Fig. 10).

Second, we also note that the ice flow divide location does not match with the topographic divide. We identified the ice flow divide location by the minimum in the ice velocity (Millan and others, 2022), which is located 1.4 km away from the topographic divide in direction of Jasgulem Glacier (Fig. 10). The location of the ice flow divide is imposed by the bed geometry. Ground penetrating radar measurements show that the glacier bed maximum elevation is not located at the topographic divide (Lambrecht and others, 2014, 2020, Fig. 10). Jasgulem Glacier is a surge-type glacier, with flow instabilities that are usually confined to the lower elevations (Goerlich and others, 2020; Guo and others, 2023). It is thus unclear whether the ice dynamics might impact the flow of Fedchenko glacier, due to their share the divide.

All the elements brought to this discussion point towards transient conditions at Jasgulem pass, but we cannot make any definitive interpretation about the surprising features observed in this study.

Uncertainties and limitations

Our analysis relies heavily on the analysis of topographic data that originates from multiple sources (historical ground photogrammetric surveys, spy satellite imagery, modern satellite imagery, satellite laser altimetry and GNSS), each referring to different geodetic reference systems, which is particularly true for the historical maps. Despite a careful processing of these data, it remains challenging to assess the uncertainty in a quantitative way, due to the lack of stable terrain. We assessed the impact of the spatial sampling in the method section, and found a moderate impact for the GNSS data, with a standard deviation of 0.34 m, and a larger impact for ICESat data, with a standard deviation of 0.54 m. We also assess the impact of the seasonal correction applied to the GNSS data. If we do not apply the correction, we find rates of elevation changes 0.06 m yr^{-1} less negative for the period 2003-2009 and 0.11 m yr^{-1} more negative for the 2016-2021 periods, respectively. These results correspond to a 25 % error, which would change the interpretation of the results if not applied. The correction is based on only one period of analysis in summer 2019, which is a limitation.

Providing highly accurate and spatially complete maps of elevation changes over large glaciers, such as Fedchenko Glacier, is a challenge, even for the most recent sensors. DEMs from SAR sensors, such as TanDEM-X allows covering large areas at once, and are thus well suited. However, they are impacted

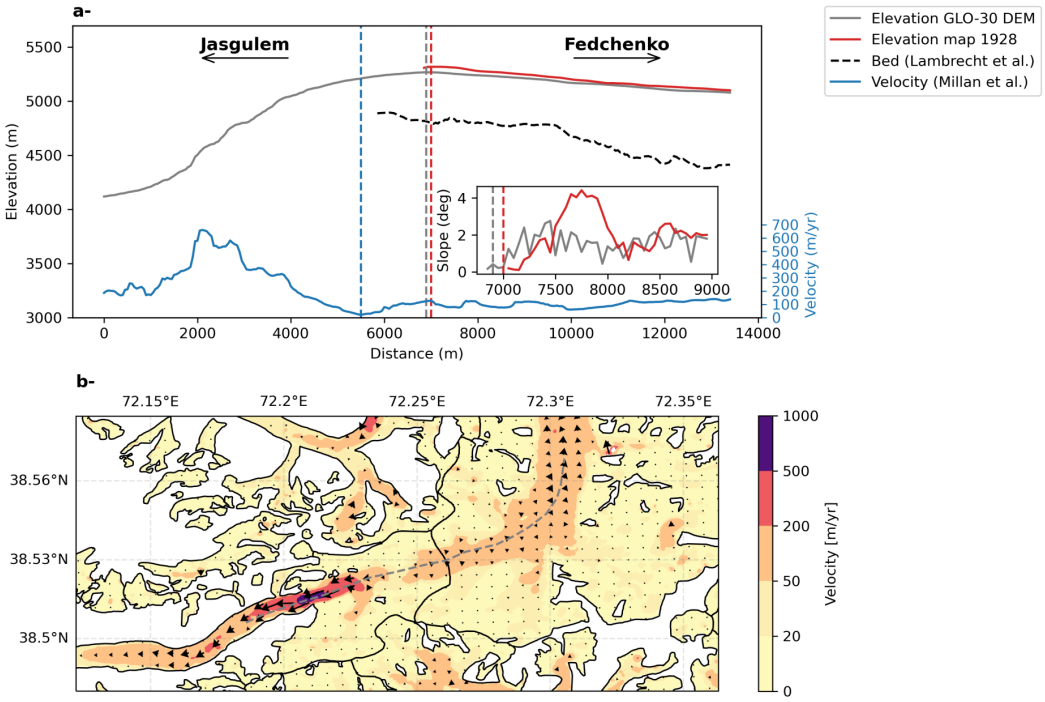

Fig. 10. Elevation and velocity along a 14 kilometre flow line crossing Jasgulem pass (a). The dashed vertical blue line show the minimum velocity (ice divide) and the dashed red and grey lines show the maximum elevation (topographic divide) in 1928 and in 2019, respectively. The Copernicus 30 m DEM (GLO-30DEM; European Space Agency, 2022) elevation is adjusted on the Pléiades 2019 elevation for consistency. The inset shows the slope within two kilometres along the flowline downstream of the topographic divide. The map (b) shows the surface velocity from Millan and others (2022) at the location of Jasgulem pass (solid black line separating the two main glaciers). The grey dashed line shows the flowline profile of panel a.

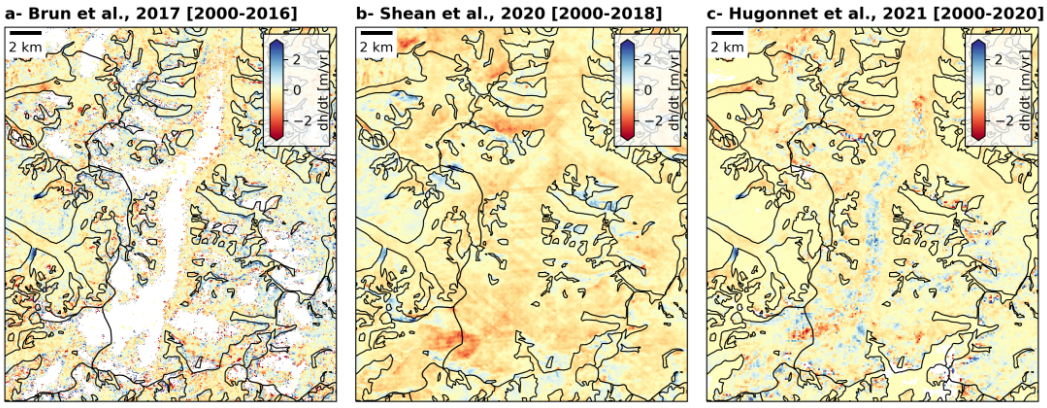

Fig. 11. Rates of elevation changes for the higher part of Fedchenko glacier from ASTER based studies (Brun and others, 2017; Shean and others, 2020; Hugonnet and others, 2021).

by the unknown penetration depth of the X-band signal (Li and others, 2021). For the specific case of Fedchenko Glacier, the X-band penetration is limited for September acquisitions for elevations below 5400 m a.s.l. (Lambrecht and others, 2018). Time series of ASTER DEMs are also used to calculate geodetic mass balances, but the image correlation shows limited success in the high elevation areas, due to the lack of texture and/or the saturation of the images. This leads to artefacts or voids in the reconstructed DEMs, and thus to highly variable rates of elevation changes for three different studies (Fig. 11; Brun and others, 2017; Shean and others, 2020; Hugonnet and others, 2021). Commercial optical sensors such as Pléiades or WorldView are less prone to saturation (Berthier and others, 2023), although it can still happen, as visible in the 1-2 August 2019 Pléiades DEM (Table 1). Thanks to their very high resolution (50 cm to 1 m of ground sampling distance) and radiometric depth, these sensors capture images with more texture than the lower resolution sensors. It is thus possible to derive void free DEMs on areas with limited or small surface features. The main limitation of these acquisitions is that they are commercial satellites, with limited user access to the tasking and to the existing archive. Another challenge is the limit of the swath width at 20 km in the case of Pléiades, leading to acquisitions distributed over multiple days to cover a larger glacier such as Fedchenko (Table 1).

In this study we rely on ERA5 data to investigate the temporal changes in meteorological conditions. Barandun and Pohl (2023) showed that relying on different meteorological reanalysis can have an impact on the relative importance of the predictors of glacier mass balance variability. As ERA5 monthly estimates of temperature, and to a lesser extent precipitation, are in good agreement with the Fedchenko station measurements, we did not investigate other data sources, but it is clear that our analysis could benefit

from long-term climate simulations that cover the twentieth century.

CONCLUSION

In this study, we document more than nine decades of elevation changes of Fedchenko Glacier from 1928 to 2021, in the heart of the data scarce Central Pamir. We use various data sources, including topographic maps, DEMs from optical satellites and GNSS surveys, allowing us to study four distinct sub-periods (1928-1958, 1958-1980, 1980-2010, 2010-2021). These topographic data are combined with meteorological data from Gorbunov Station (1936-1994) and ERA5 (1950-2021). Overall, we observe an up-glacier propagation of the thinning rates, that are the largest for the most recent period of observation (2010-2021). In particular, thinning rates of the accumulation basin reach -0.41 m yr^{-1} for the period 2016-2021. For some periods it is possible to link the glacier rate of elevation change to climate anomalies. The period 1980-2010 shows limited thinning, and even thickening in the accumulation area. This periods corresponds to a wet anomaly that might have limited mass loss. Still, the temporal variability in the rates of elevation changes cannot be fully linked to the climate variability. For instance, for the period 1958-1980, we observe large thinning on the tongue of Fedchenko Glacier that seems to be link to anomalously high velocities. This example shows the limitation of relying on non complete maps of elevation changes to investigate glacier mass changes.

ACKNOWLEDGEMENTS

We thank Sajid Ghuffar for sharing the 1968 Corona KH-4 orthoimage and DEM. EB acknowledges support from the French Space Agency (CNES).

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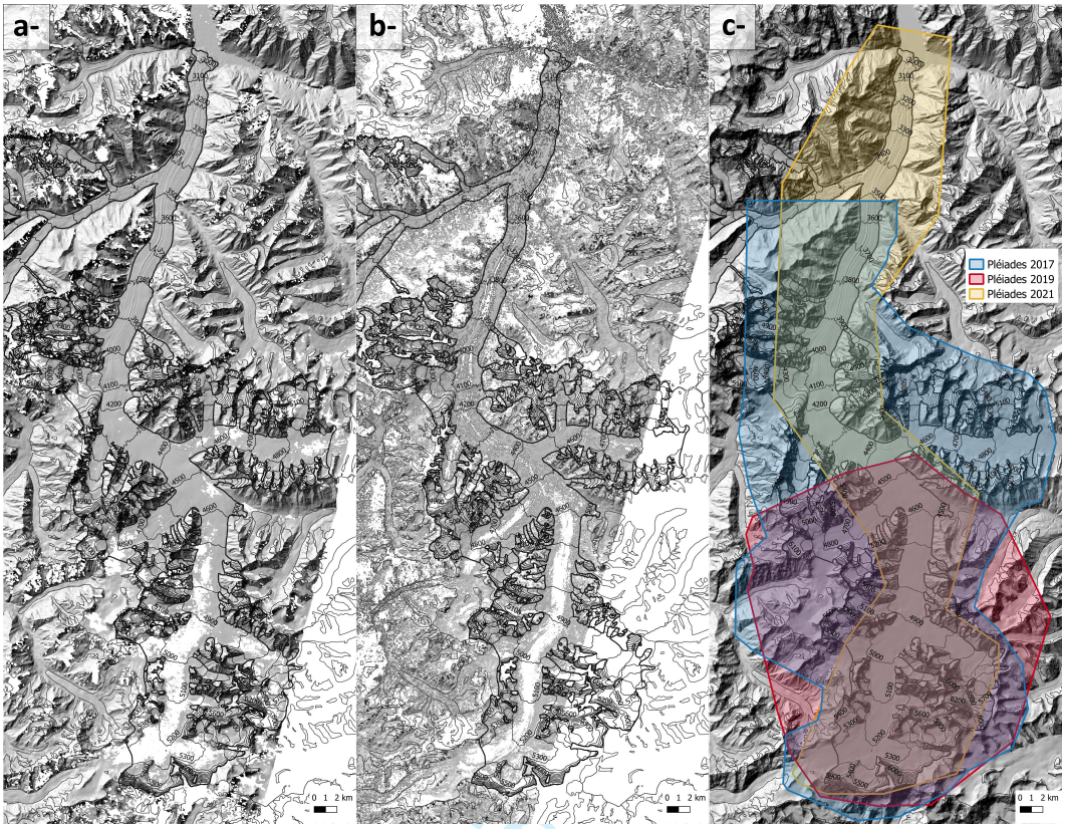

Fig. A1. Hillshades from the KH-9 (a) and SPOT 5 (b) DEMs. Panel c shows the footprint of the different Pléiades DEMs.

APPENDIX

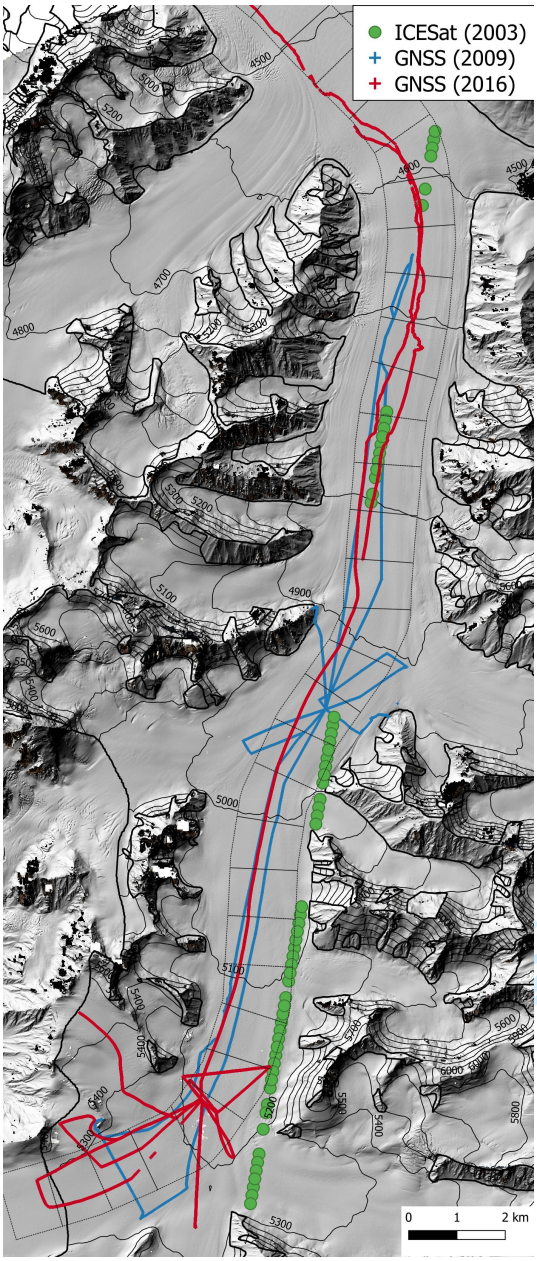

Fig. A2. Summary of the ICESat and GNSS acquisitions

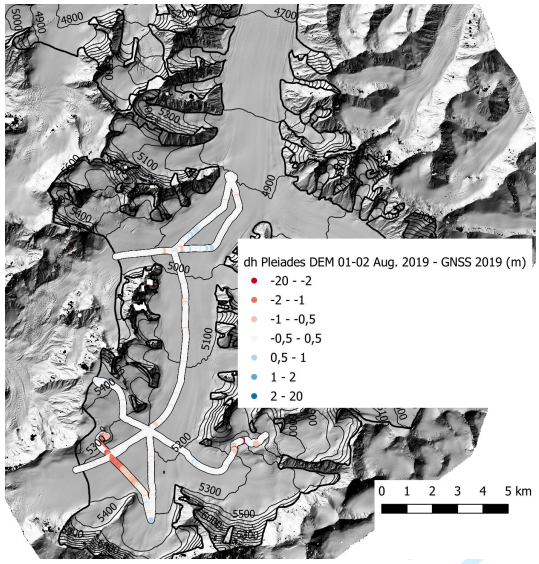

Fig. A3. Elevation difference between GNSS measurements and the avarage between the Pléiades DEMs of 1-2 and 28-29 August 2019 after co-registration. Note some spurious measurements in one GNSS track that was discarded from the analysis.

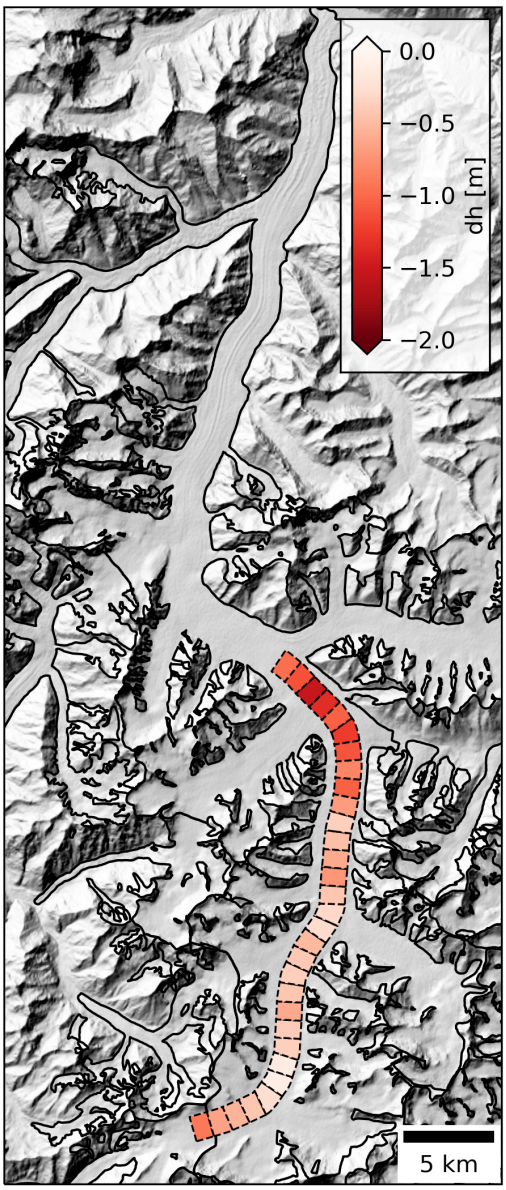

Fig. A4. Elevation difference between the Pléiades DEM of 22-23 September 2019 and the Pléiades DEM of 1-2 August 2019 that is used for the seasonal correction of GNSS data.

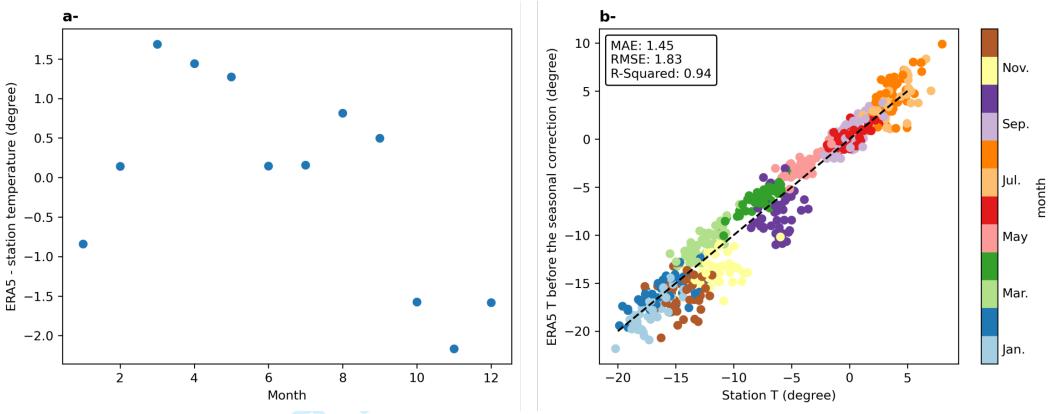

Fig. A5. Mean monthly temperature bias in ERA5 data (a) and monthly ERA5 versus the station temperature before seasonal bias correction (b).

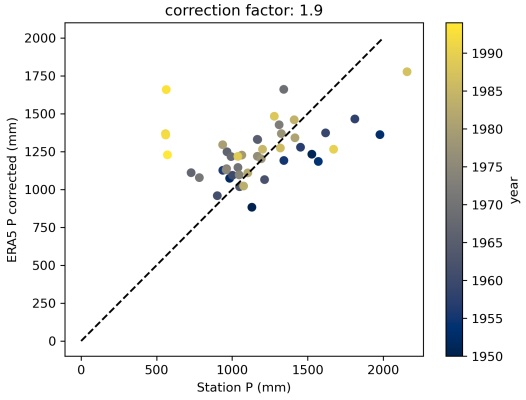

Fig. A6. Comparison of the annual ERA5 adjusted precipitation the annual station record for the overlapping years (1950-1994). Note the spurious values for the years 1990 to 1994 in the station record. These values were excluded from the analysis.

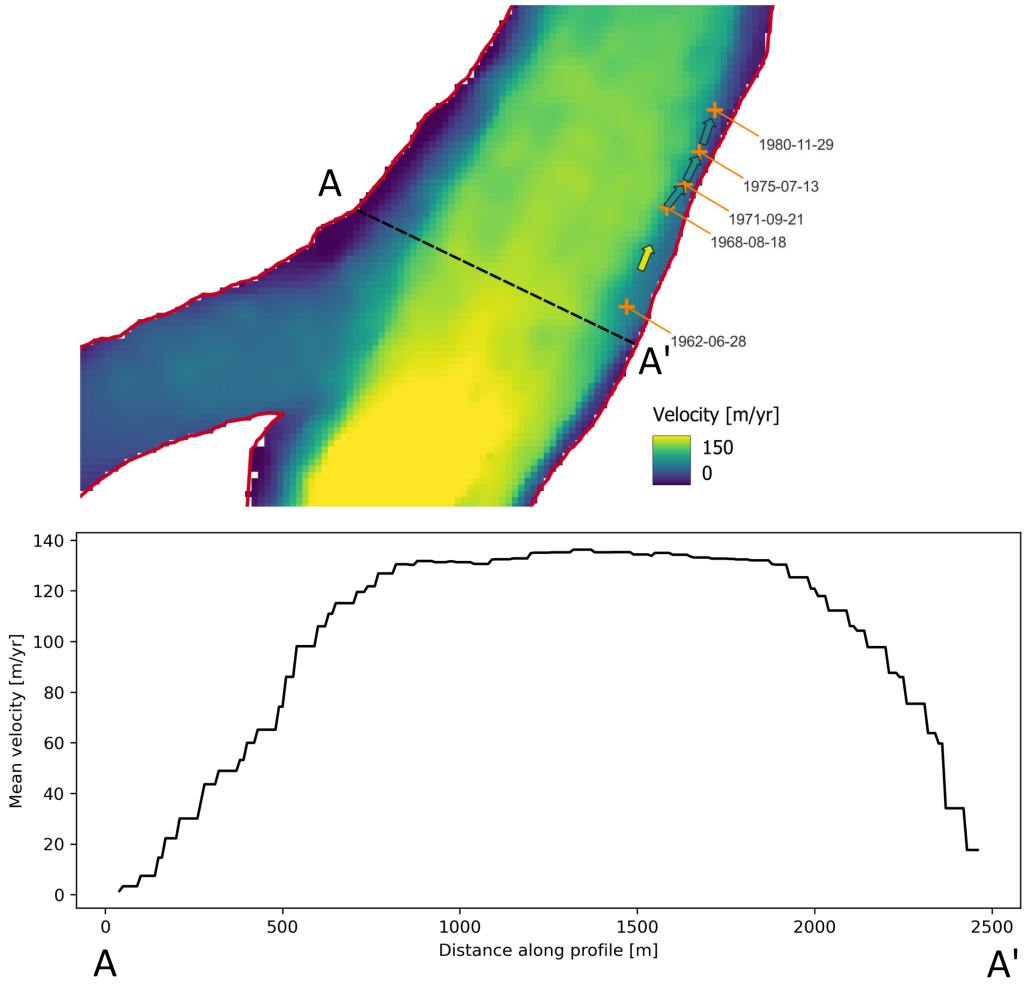

Fig. A7. Map of the location of the tip of the looped moraine identified in the spy satellite imagery (Table 4 and Fig. 9). The background is the velocity map from Millan and others (2022), and the arrows show the velocity inferred from the looped-moraine tracking. The graph shows the velocity profile along the AA' line (corresponding to the approximate location of the X profile) from Millan and others (2022).