Garabashi glacier (Caucasus) mass changes estimated from glaciological and geodetic mass balance measurements

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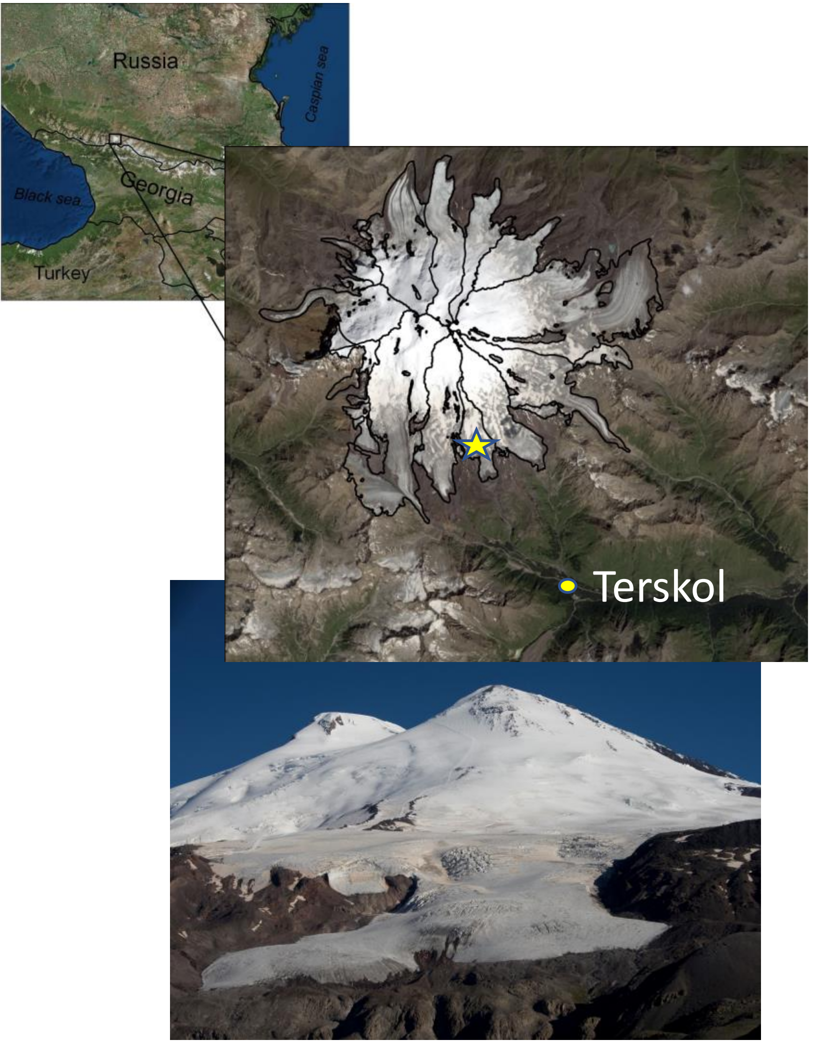

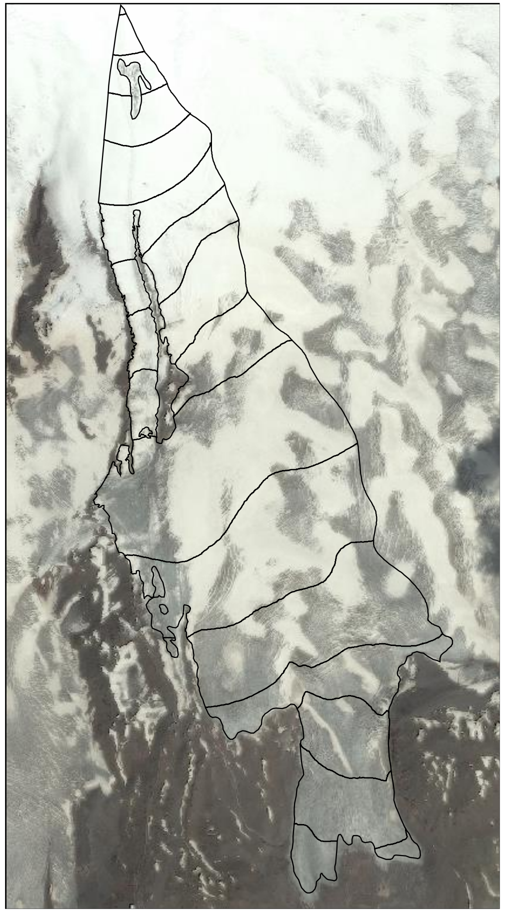

The ice-covered Europe's largest volcanic massif Elbrus (5,642 m) is a unique object for studying the reaction of mountain glaciers to climate changes. Elbrus glaciers influence on the recreation development. The rivers runoff from the Elbrus glaciers irrigates agricultural lands on steppe plains of the North Caucasus.

Here we present the results of the detailed analysis of Garabashi glacier mass changes in 1982-2019 using glaciological and geodetic methods. Based on the new data of snow and ablation distribution the mass balance measurement system of Garabashi glacier was improved in 2018-2019. The mass balance over the studied period was also modelled using both temperature-index and distributed energy mass balance models.

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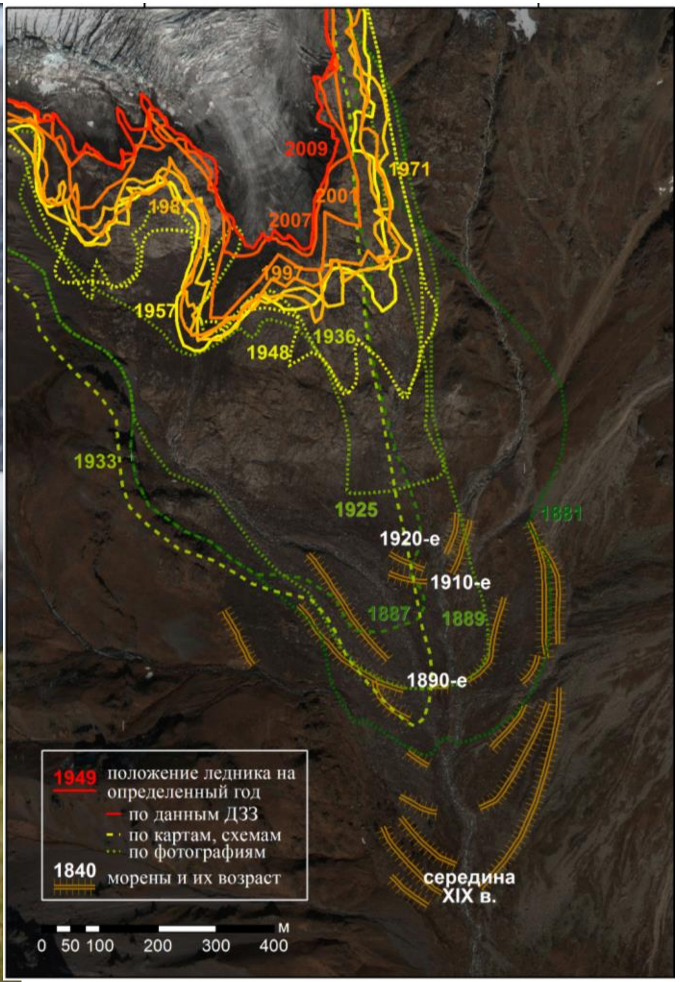
Glacier changes in Caucasus

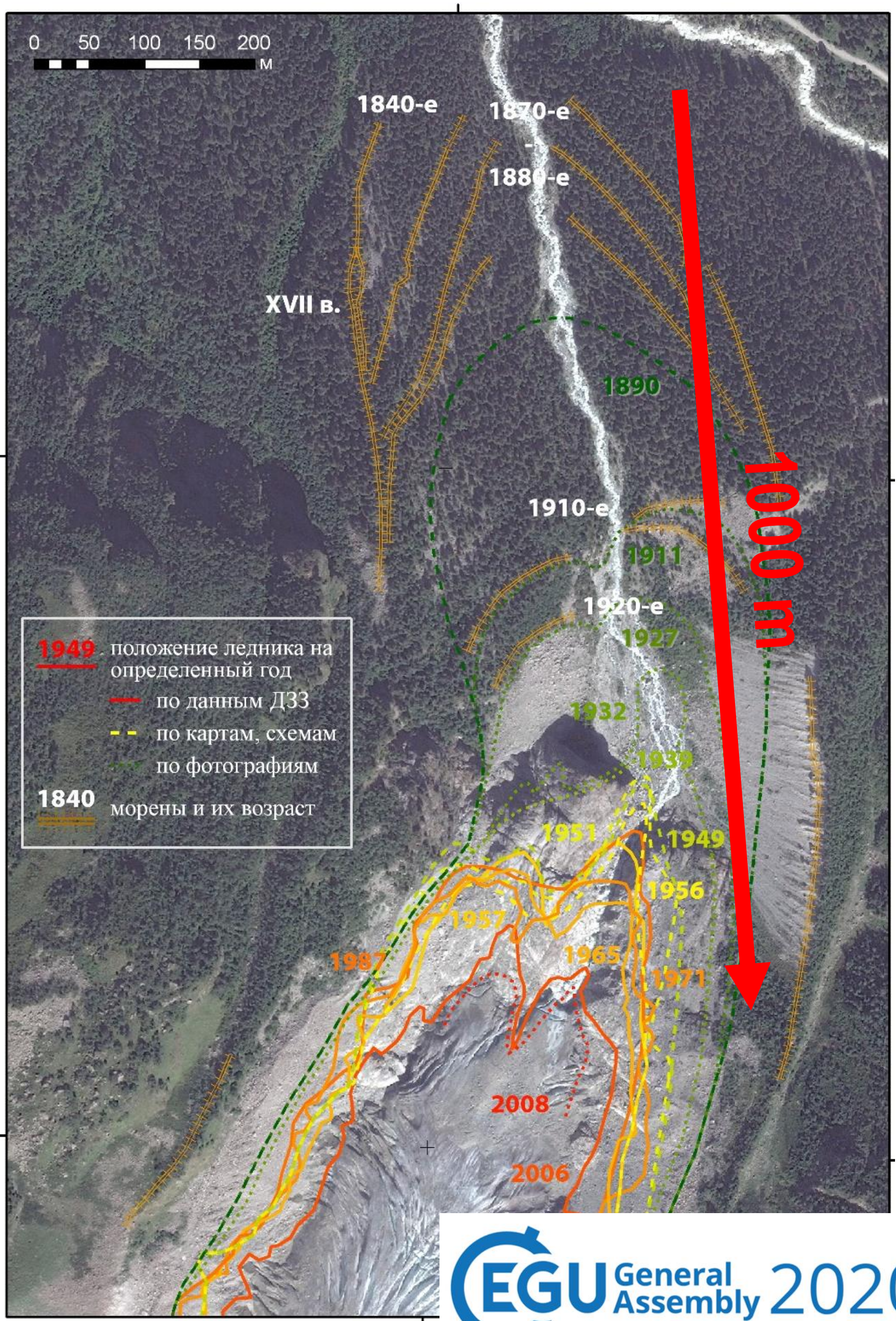
Solomina et al., 2016

- The maximum glacier extent in the past millennium was reached before 1598 CE;
- General glacier retreat started in the late 1840s CE and four to five minor readvances occurred in the 1860s–1880s CE.
- In the 20th century CE, the continued retreat was interrupted by small readvances in the 1910s, 1920s and 1970s–1980s.
- Over the past 500 years there is a very good coherency between the climate and glacier variations in the Alps and Caucasus.
- Since the LIA maximum in the middle of 19th century CE, glacier lengths have decreased by more than 1000 m, and front elevations have risen by more than 200 m.



Terskol glacier

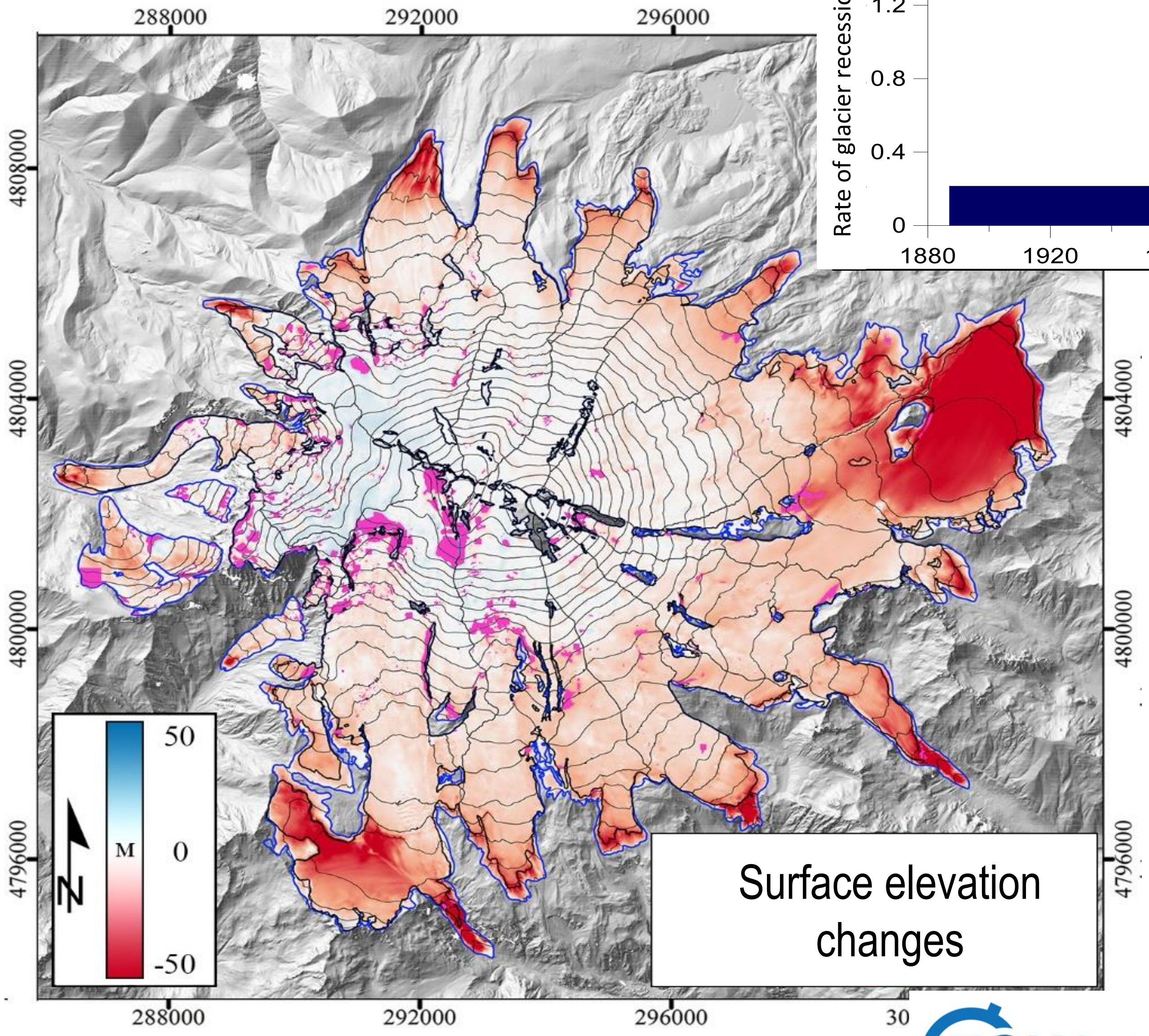
Kashkatash glacier, Central Caucasus. (Bushueva et al., 2015)

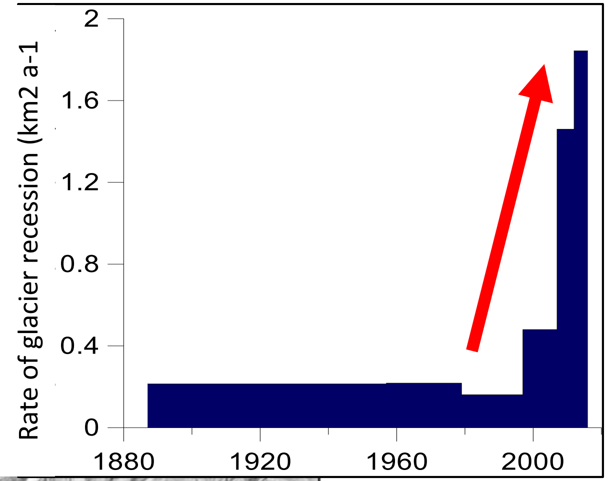


Elbrus glacier system

(Kutuzov et al., 2019)

- Volume reduction by **23% in 1997-2017**.
- Surface lowering up to 80 m.
- Rate of glacier mass loss in 1997-2017 has **tripled** compare to 1957-1997 period
- Sharp increase in glacier recession rates since 2000s





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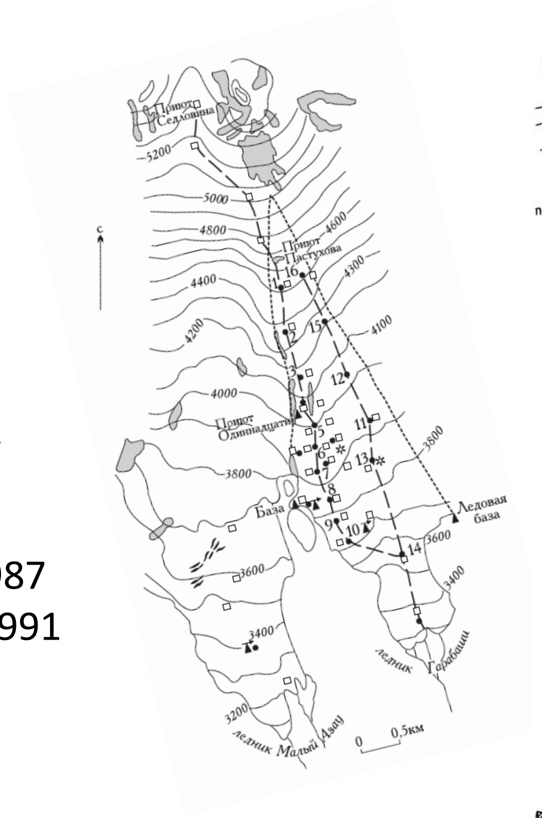
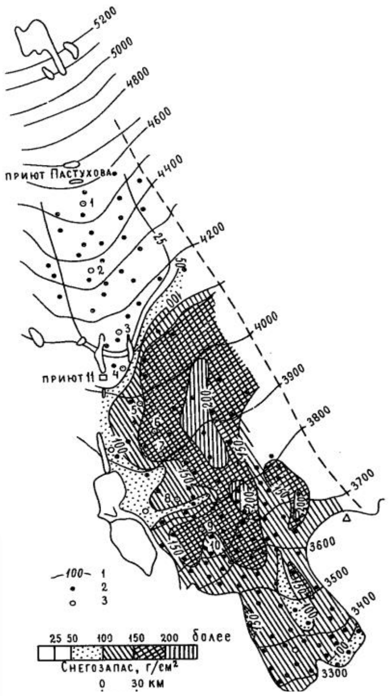
Garabashi glacier

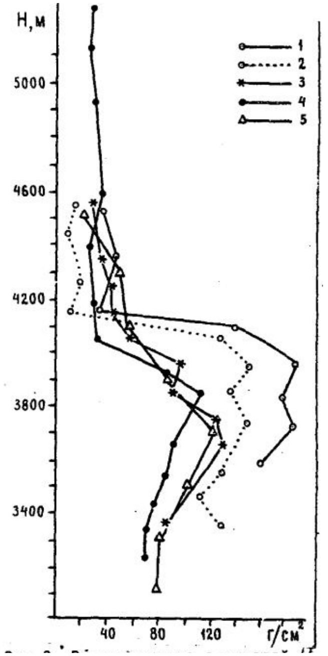
Research base of IGRAN and KSC KBR from 1987 г.

First measurements - 1982
Regular measurements - since 1987
Detailed measurements - 1987-1991

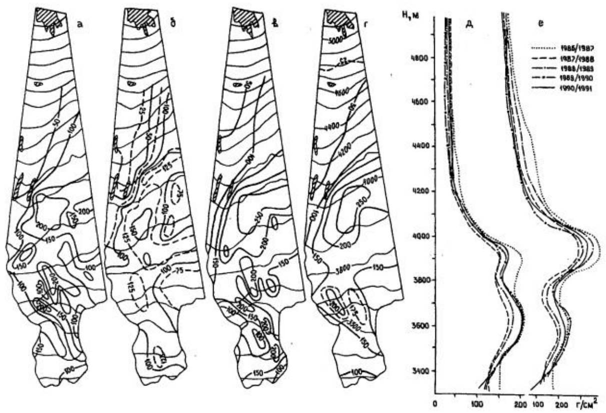




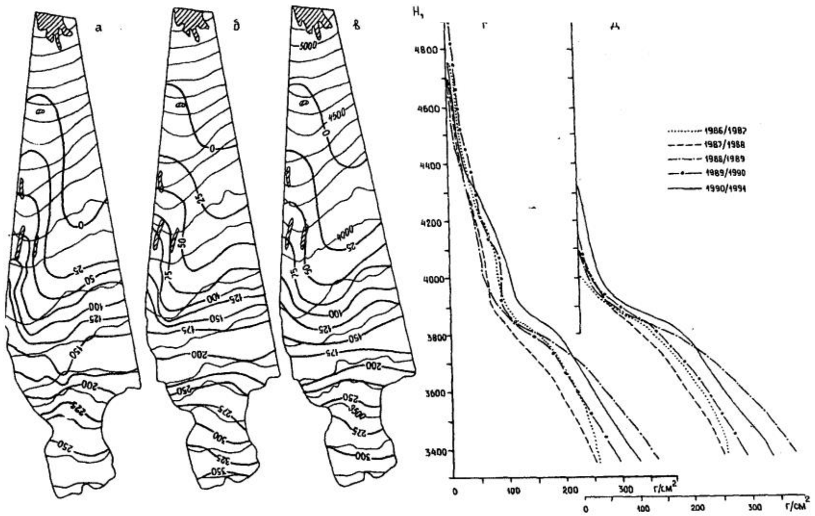
Snow accumulation in May 1987



Snow accumulation vs elevation 1984-1987



Accumulation distribution

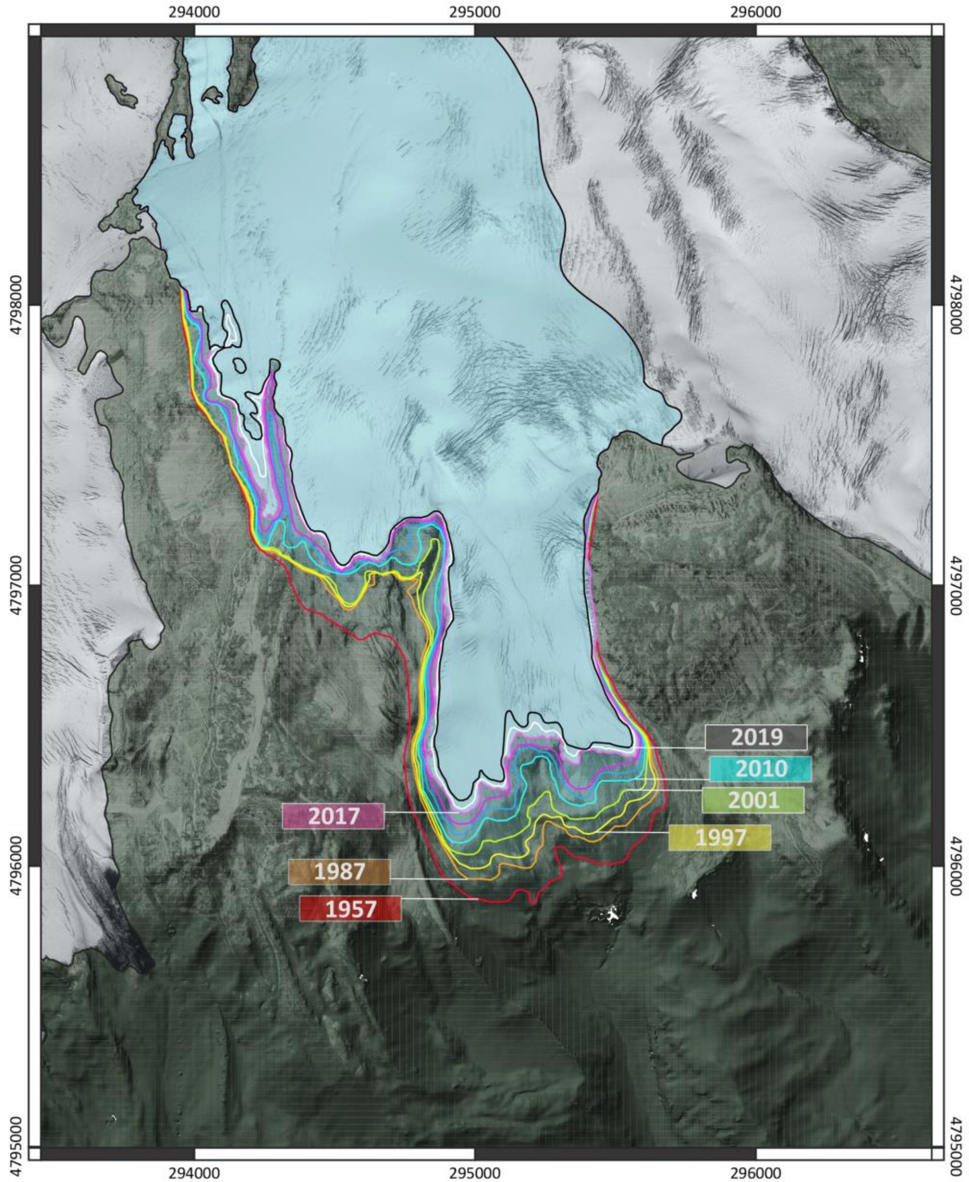


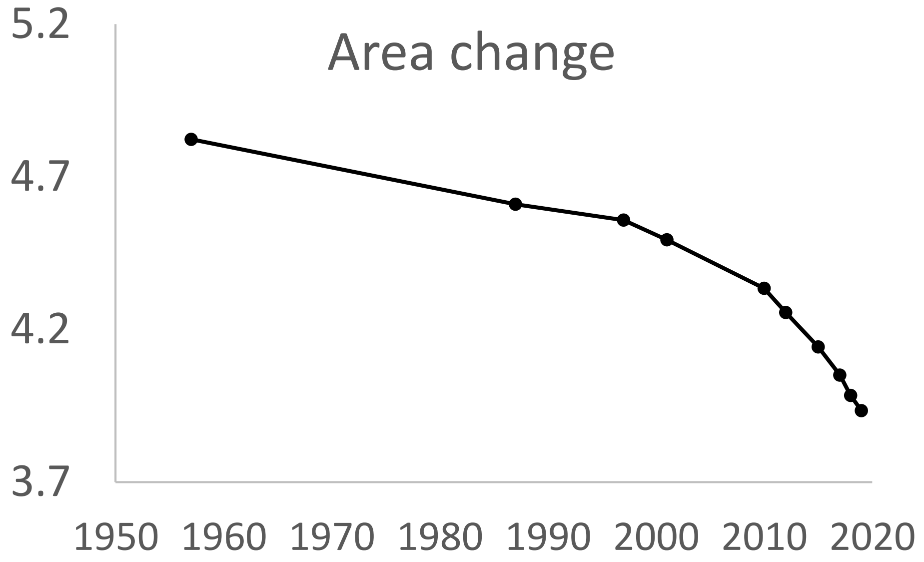
Ablation distribution

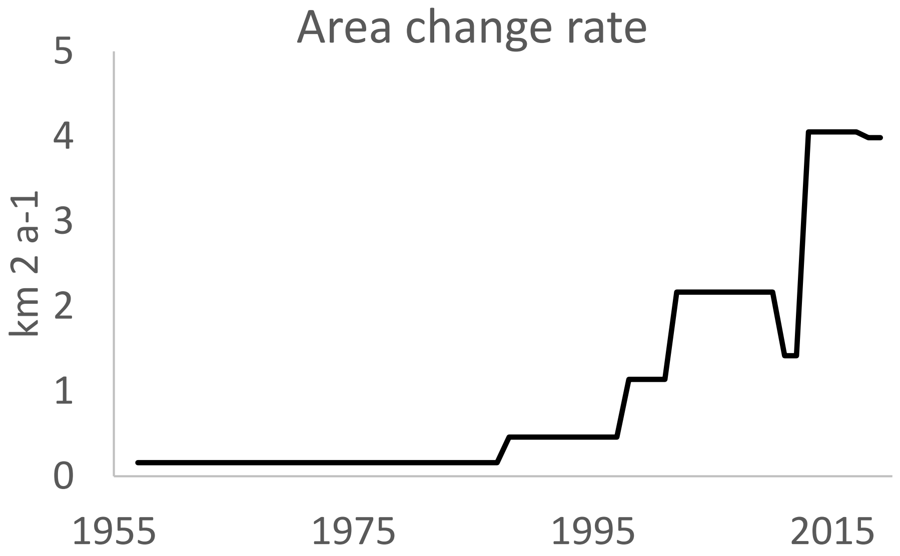
Despite a number of glacier studies the mechanisms and quantitative characteristics surface mass exchange on Elbrus are still uncertain. Mass balance calculations were based on limited data.

In particular, amount and distribution of snow accumulation, mass balance sensitivity to meteorological parameters under dramatic climate changes and other parameters remained unknown.

Garabashi glacier area changes

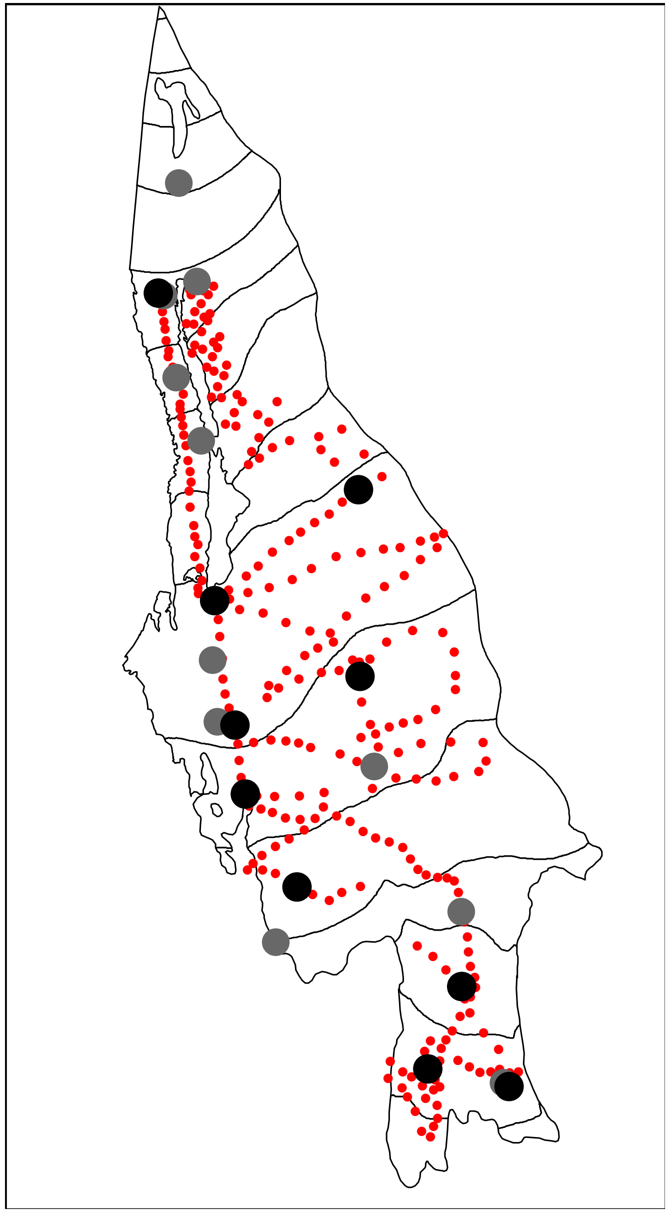






Glacier lost 18% of its area since 1957

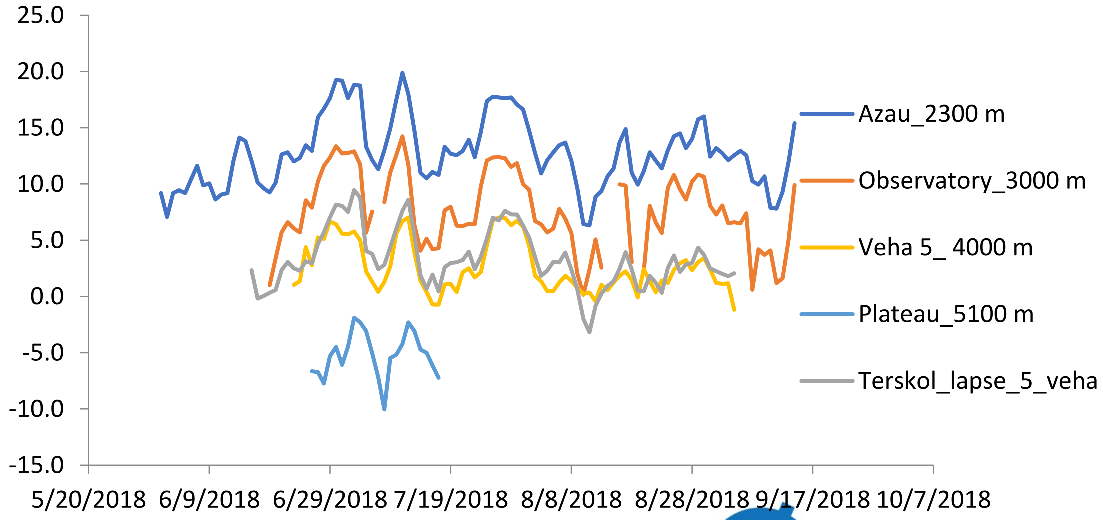
14% since 1997



The mass balance measurement system of Garabashi glacier was improved in 2018-2019.

Accumulation distribution was obtained using observations at 264 points of snow probing on May 27-28, 2019. The snow density was measured in pits and cores and was in the range 0.45-0.65 g / cm3.

Temperature is measured at 5 different elevations during ablation season



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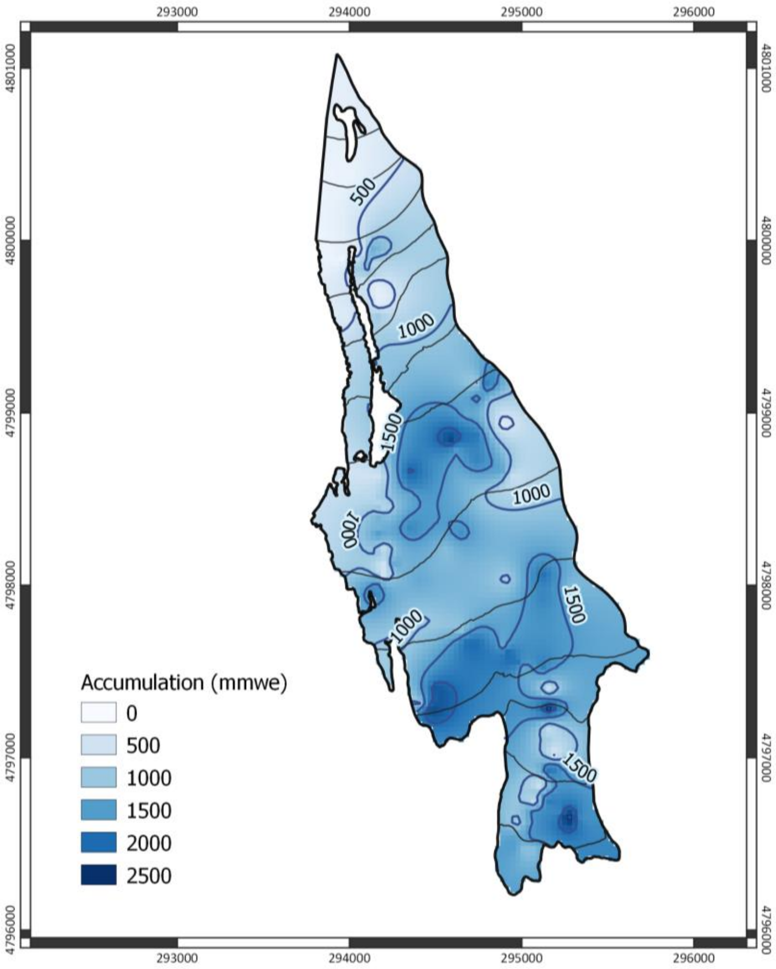
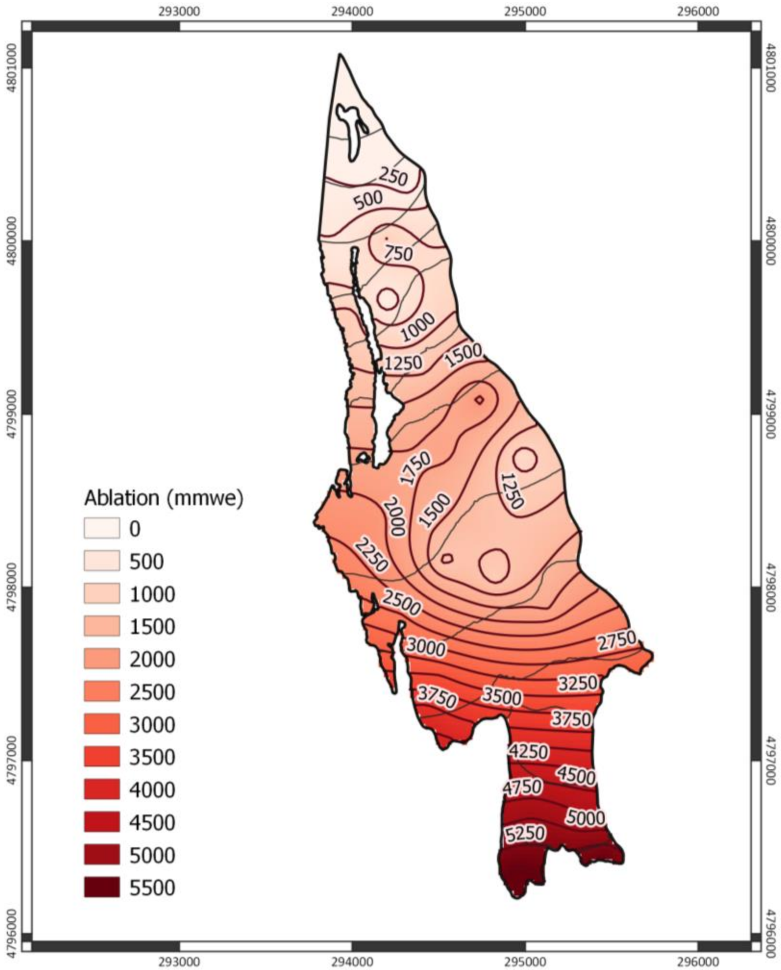
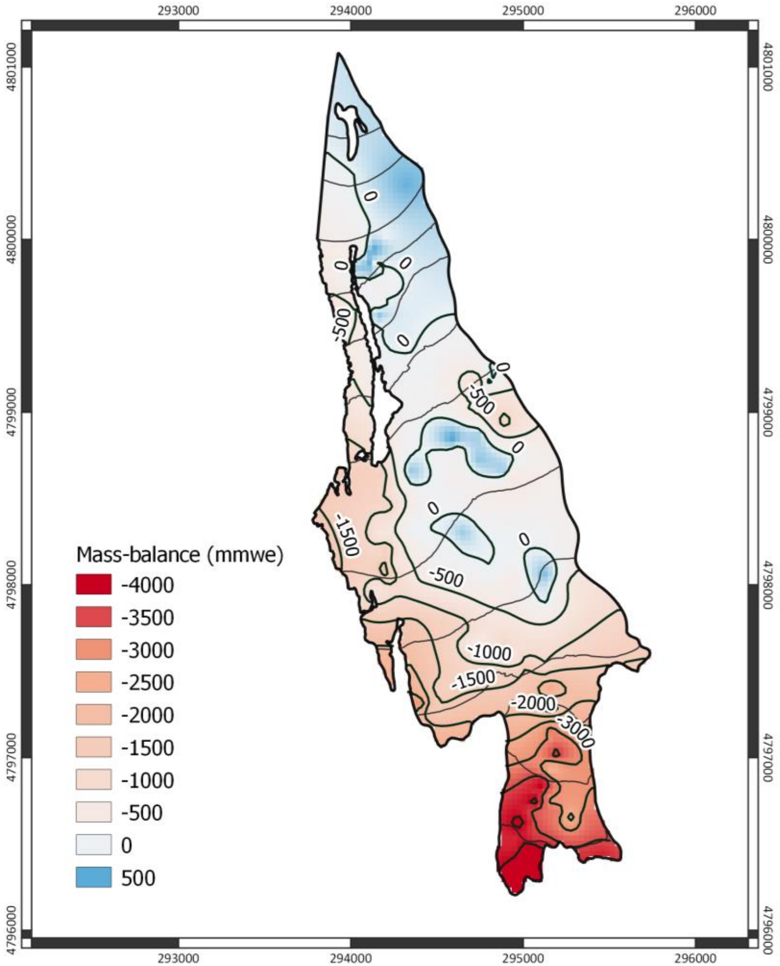
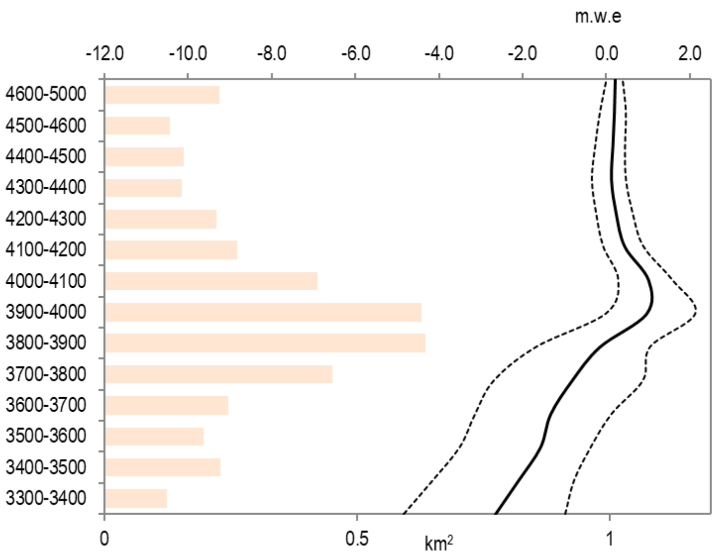
Mass balance fields of 2018/2019



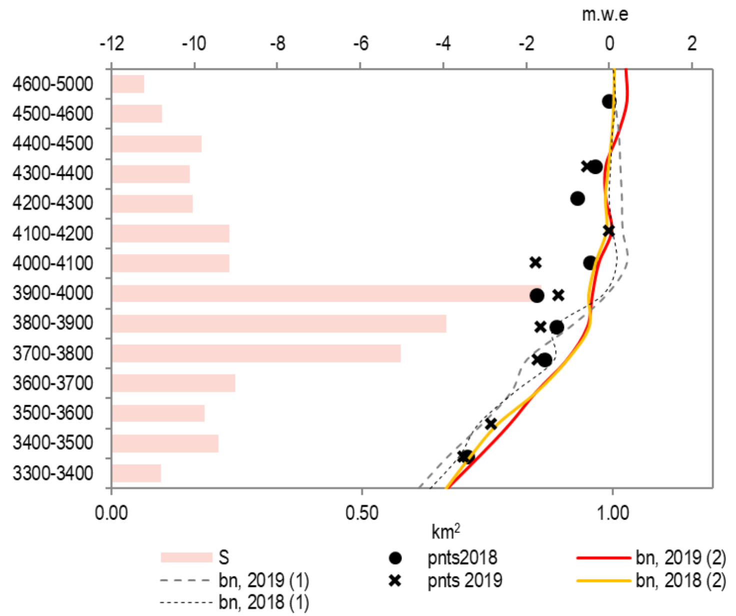




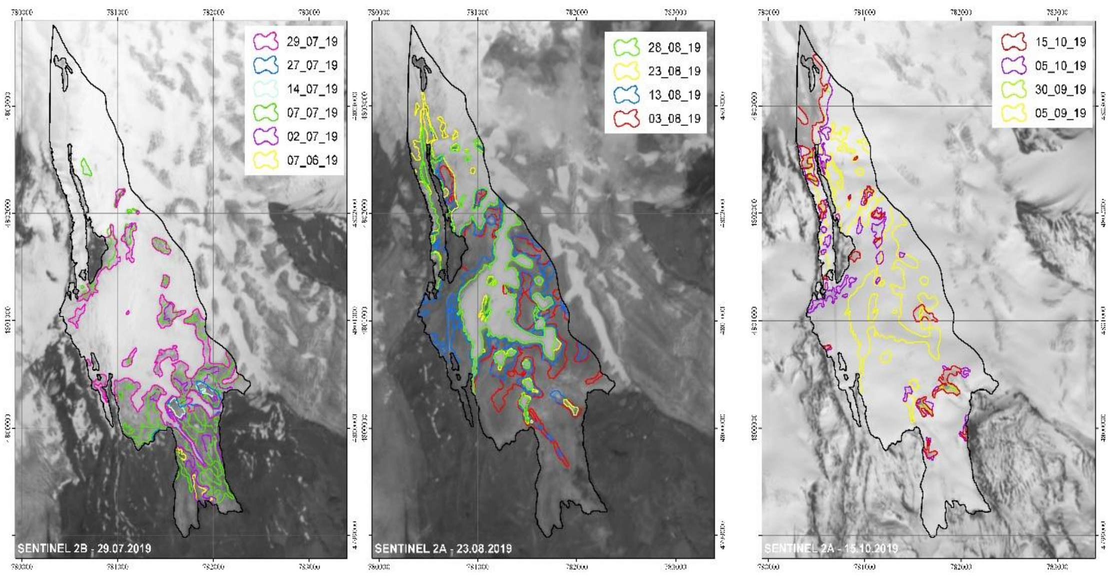
The average snow thickness was 1.83 m, and the total accumulation was 1.06 mwe. Unlike accumulation, the distribution of melting has a clear altitude dependence. The average ablation value calculated from data from 8 stakes was 1.89 mwe. The resulted mass balance of the Garabashi glacier in 2019 amounted to -0.83 mwe.

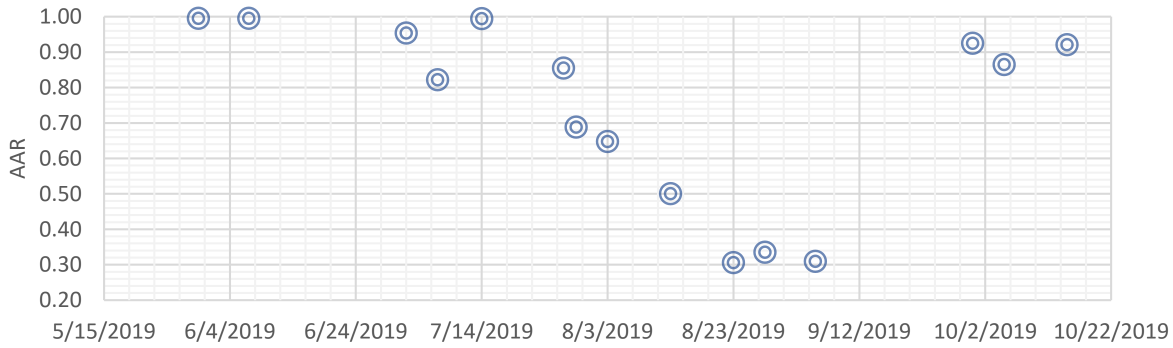


Mb in 1982-2019



The results of observations were interpolated over the entire area of the glacier. At the same time, the traditional calculation of the mb (profile) was also applied. Unlike accumulation, the distribution of melting has a clear altitude dependence, however, in recent years a new area has been identified with increased melting (stake 5 4000 masl). The ablation values calculated by the two methods give close values of -1.89 mm.e. (interpolation (2), -1.88 (profile method (1)





A study of the dynamics of the snow border was carried out using 14 Sentinel images. As a result, it was possible to determine the minimum area of snow coverage that coincides with the ELA (1.2 km2) and to trace the change in the area of snow cover on the glacier during the summer. By August 23, AAR had reached a minimum of 0.3.

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TI modeling:

Here we apply a temperature-index model (Braithwaite and Zhang, 2000) together with an accumulation model to calculate the mass balance. Ablation is related to the positive degree-day sum and accumulation is estimated from solid precipitation on the glacier surface. Snow accumulation at any particular altitude is estimated by assuming that precipitation is split between rain and snow near the threshold temperature (1°C). Rain is assumed to run off the glacier and not to contribute to the mass balance:

$$A = \begin{cases} DDF_{ice/snow}T & : T > 0°C \\ 0 & : T \leq 0°C \end{cases}$$

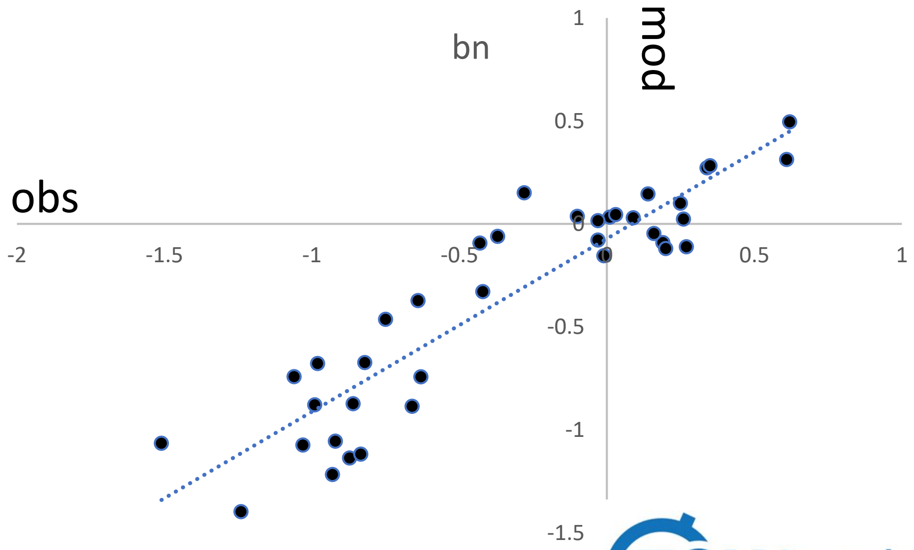
$$C = \begin{cases} C_{prec}P & : T \leq 1°C \\ 0 & : T > 1°C \end{cases}$$

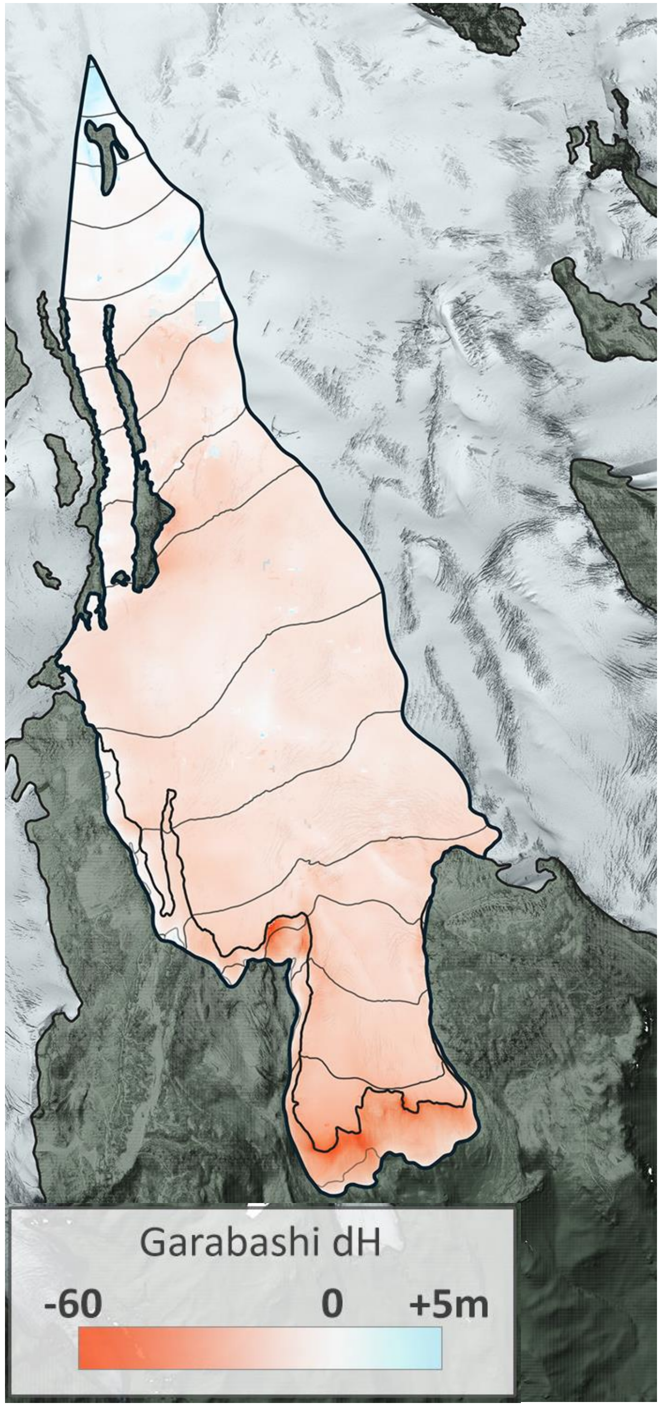
Sums of positive temperatures were calculated for every elevation band using fixed temperature lapse rate of 0.5 °C (100m)$^{-1}$. C_{prec} was adopted for the calibration of precipitation. The temperature-index model was calibrated to fit the measured data by adjusting the degree-day factors for snow and ice.

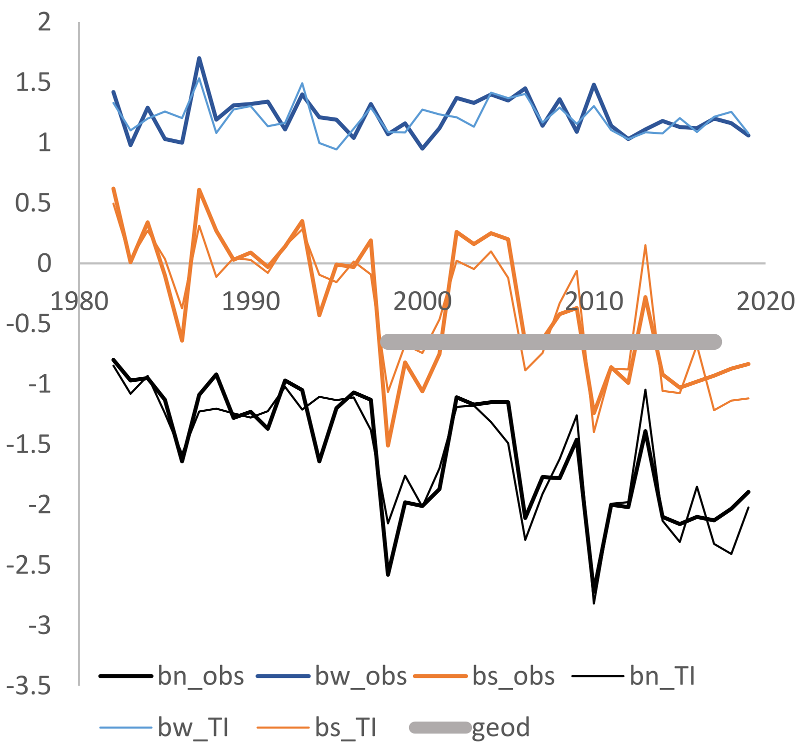
It was estimated that the best fit with the observation can be achieved using DDFs changing for three periods

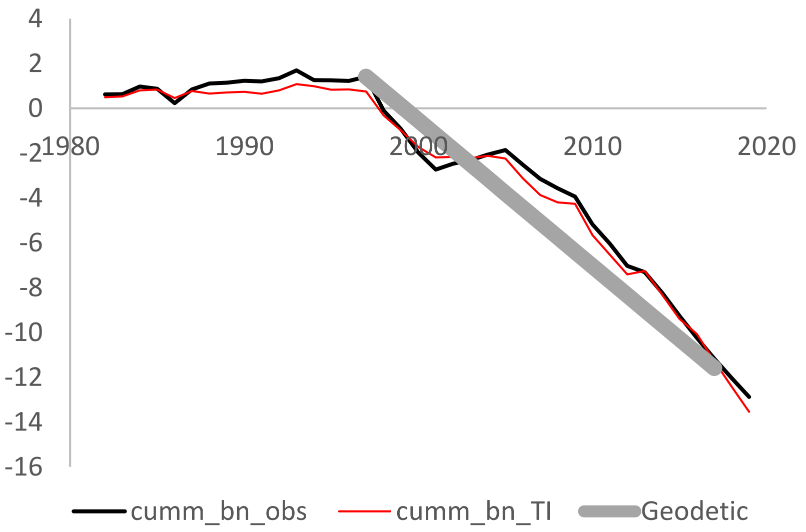
Tuning parameters	1982-1996	1997-2009	2009-2019	Unit
DDF ice	5.2	6	7	mm °C^{-1} d^{-1}
DDF snow	2	2.5	2.5	mm °C^{-1} d^{-1}

This can be explained by the increase of the incoming shortwave radiation and increase in energy balance of the glacier in recent decades.





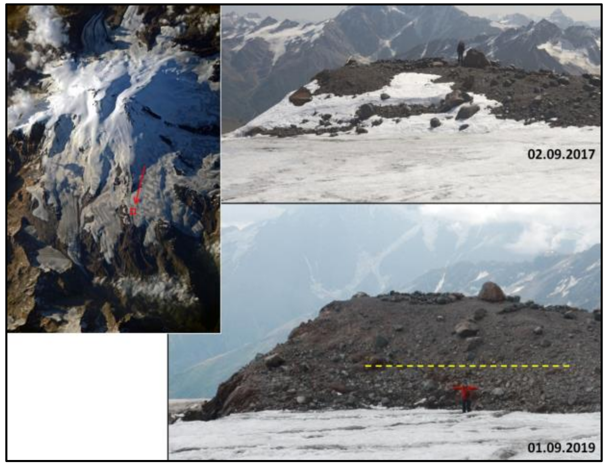




Comparison with the geodetic MB 1997-2017

Glacier-wide and
cumulative mass balance show a good agreement for the period 1997-2017. Garabashi glacier lost

- 12.58 m w.e. (−0.63 w.e. a-1) estimated by glaciological method and
- 12.92 ± 0.95m w.e. −0.65 ± 0.05m w.e. a-1) estimated by geodetic method (DEM 1997 – aerial photographs, DEM 2017 – Pleiades).



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Main factors of glacier degradation in Caucasus

- Increase in summer temperature by 0.6-0.8 C per decade

- Increase in shortwave radiation balance by 10 W/m2 per decade (Toropov et al., 2019

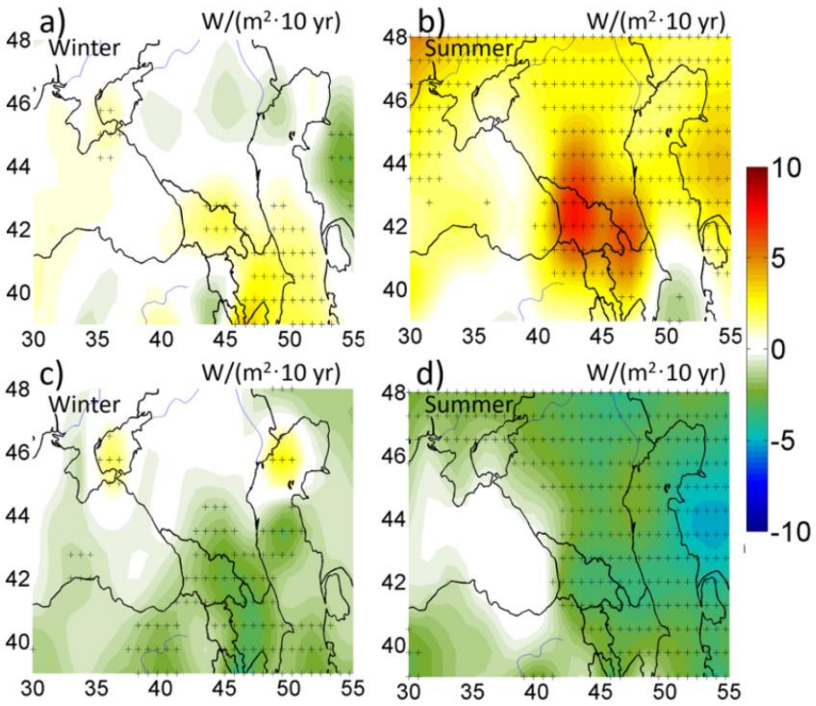
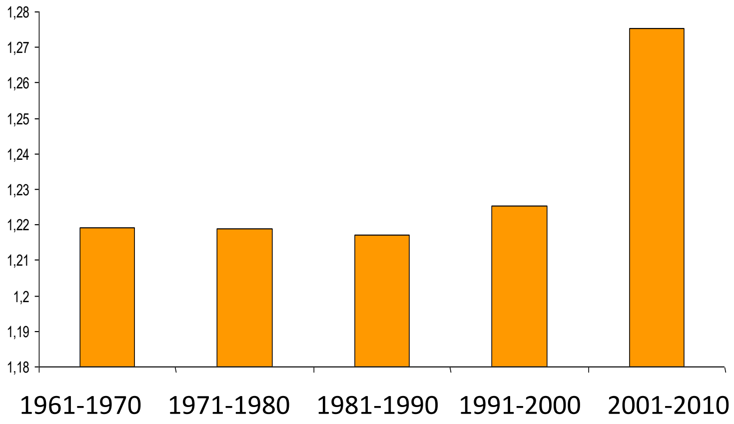
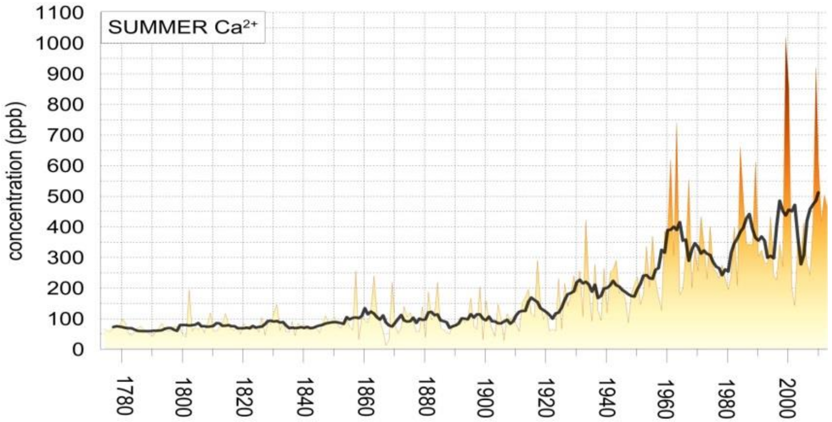


Figure 8. The trends in the radiation balance components according to the ERA-Interim reanalysis data: A, B - shortwave balance (the difference between the descending and ascending short-wave radiation); C, D - longwave balance (the difference between the descending and the ascending longwave radiation); A, C - winter, B, D-summer.

- Increase in radiation budjet by 4% (Toropov et al ., 2015)



- Increase in dust concentraion by 4 times since 1900s (Kutuzov et al., 2019



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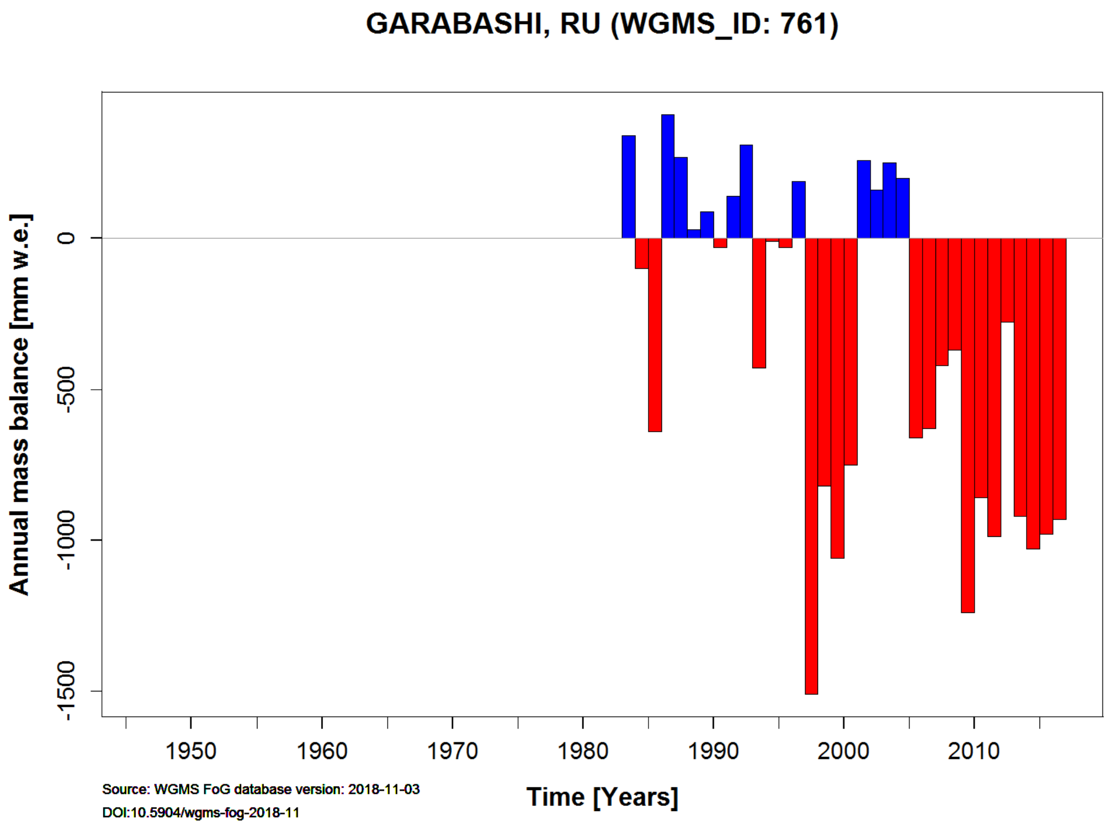
Conclusions



The mass balance of the Garabashi glacier was close to zero or slightly positive in 1982-1997 and the cumulative mass balance was 1 m w.e. in this period.

In 1997-2017 Garabashi glacier lost 12.58 m w.e. and 12.92 ± 0.95 m w.e. (−0.63 and −0.65 ± 0.05 m w.e. a−1) estimated by glaciological and geodetic method, respectively. Additional -1.7 m w.e. were lost in 2018-2019.

This resulted in an area reduction by 14% and a loss of 27% of glacier volume.

The observed glacier recession is driven by the pronounced increase in summer temperatures, especially since 1995, which is accompanied by nearly consistent precipitation rates The increase in incoming shortwave radiation, also played a significant role in the accelerated mass loss of glaciers in Caucasus.

New mass balance measurement system was improved. Garabashi glacier is listed among the reference glaciers since 2020.