On The Trail of the Glaciers

CAUCASUS 2011

SCIENTIFIC RESULTS

Riccardo Scotti

(with the cooperation of Kenneth Hewitt, Claudio Smiraglia and Fabiano Ventura)

Recent length and surface variations of Chaalat, Adish and Tviber glaciers

(Enguri river basin, Georgia, Caucasus)

1 INTRODUCTION

Caucasus Mountains, running west-northwest to east-southeast between the Black Sea and the Caspian Sea and separating southwestern Russia from Georgia (Volodicheva, 2002) are covered by glaciers for around 1600 km² (estimates range from 1400 to 1805 km²; Bedford and Barry, 1994). There is widespread evidence of glacier recession in this region since the end of the Little Ice Age (LIA); (Solomina, 2000), but information concerning the latter stages of the 20th century and beginning of 21th century is limited. Of the few studies that have focused on glacier change in the Caucasus, Bedford and Barry (1994) reported a strong retreat trend for 51 glaciers between 1972 and 1986. Later Stokes & al. (2006) reported that 94 % of a sample of 113 glaciers showed a terminus retreat between 1985 and 2000.

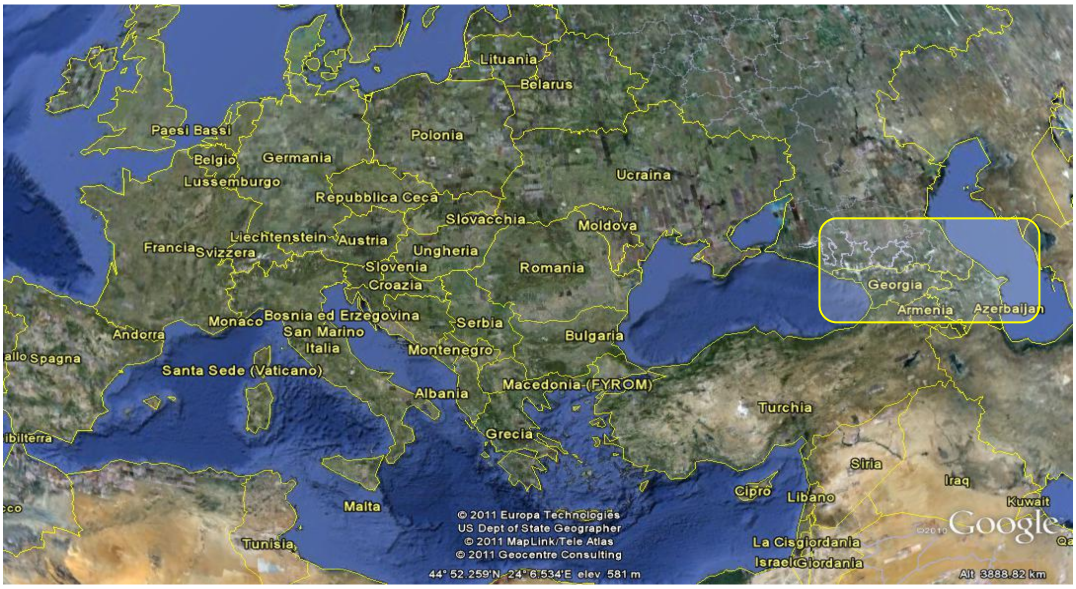


Fig. 1: The Caucasus mountain chain location between the Black and the Caspian Sea

Remote sensing is an ideal tool for increasing the number of monitored glaciers at the global scale, especially in remote or politically sensitive areas. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) are widely recognized as highly valuable for glacier mapping (Bayr and others, 1994; Paul, 2000, 2002; Paul and others, 2002). A single scene has a spatial coverage of 180km by 180 km, and the high resolution of the sensor (30 m) permits accurate monitoring of small glaciers > 0.1 km2 (Paul and others, 2002).

Fig. 2: The Adish glacier in 1889 (V. Sella) and in 2011 (F. Ventura)

Fig. 3: Recording the terminus position of the Adish glacier with a GPS device, august 2011. Picture Ken Hewitt

Fig. 4: the Enguri hydroelectric dam. Its average annual capacity is 3.8 billion kW/h, which is approximately 46% of the total electricity supply in Georgia as of 2007 (http://www.minenergy.gov.ge/index.php?m=349 Ministry of Energy of Georgia.

2 Methodology

In this study, TM and ETM+ are used to map the terminus position and to measure the area of 3 glaciers in the upper part of the Enguri river basin in 2011.The comparison of this data set with different other sources: Soviet maps from 1965, Reeves & Freshfield map from 1889 and field work surveys to determinate the maximum extend in the LIA, have permitted a solid reconstruction of the glaciers fluctuations during the last two centuries.

A field work expedition during august 2011 supported this study with high resolution terrain pictures from the exact same geographic position of pictures shoot by the first explorers in the late 19th century. The GPS position of the terminus and the frontal moraines of 3 glaciers has been recorded.

Fig. 5: The Caucasus range and the study area in Upper Svaneti – Enguri river basin - Georgia - South Caucasus. Source wikipedia

Analysis in this study involves manual delineation of glaciers using both a false-color composite of TM bands 5, 4 and 3 and single bands 1,2,3 and 5. Some ETM+ band 8 panchromatic images has been used for drawing the terminus position of the glaciers in different years. The spatial resolution is 30 m for the TM and 15 m for the panchromatic ETM+.

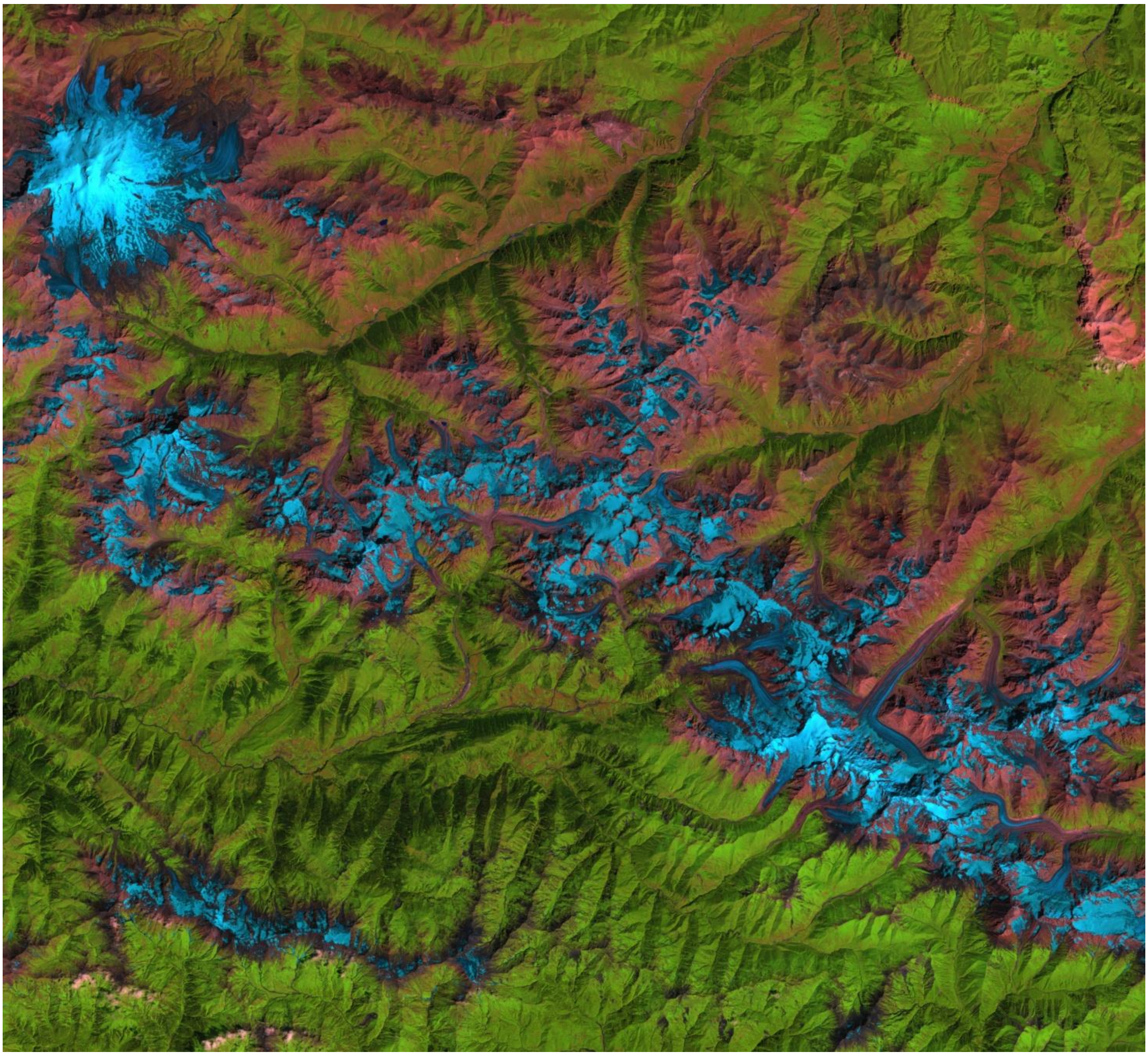
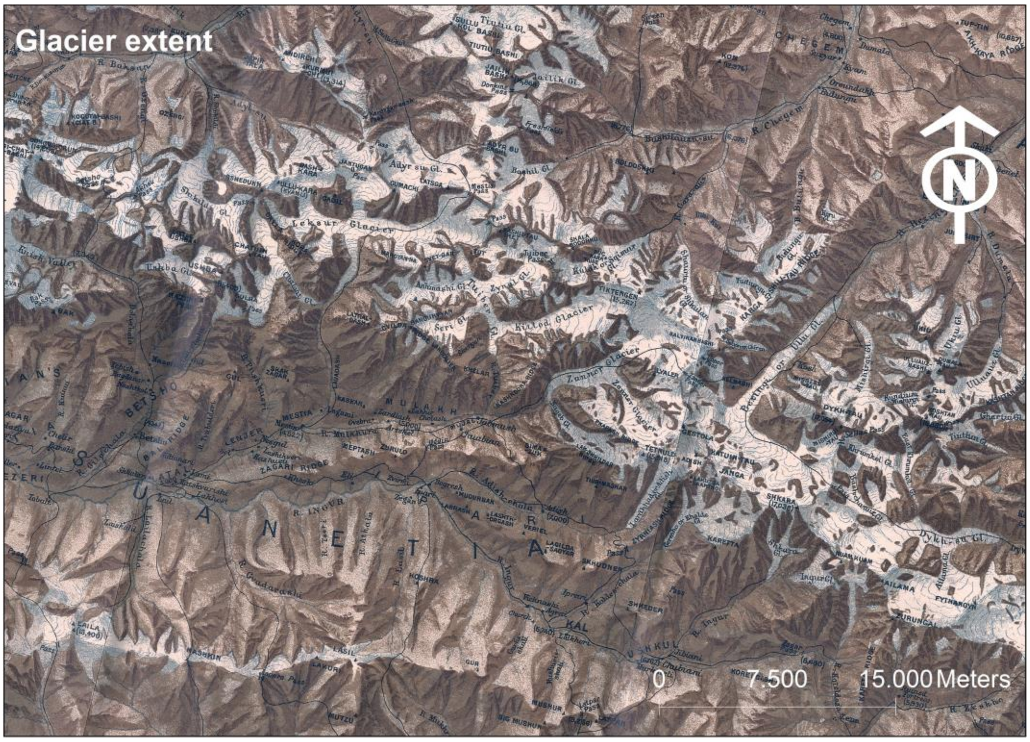


Fig. 6: A crop of the false-color composite of TM bands 5, 4 and 3 of the study area. Image from 2011.08.11, filtered with ADOBE Photoshop.

Having selected the path and row for our study area, image selection was guided by the following principles (cf. Paul and others, 2002): (a) the scenes are obtained close to or at the end of the ablation season, minimizing potential complication from seasonal snow accumulation, and (b) scenes are obtained during cloud-free conditions. Imagery was obtained from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility, University of Maryland, MD, USA (http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp) and from the United States Geological Survey (USGS) Earth Resources Observation Center (EROS) (http://edc.usgs.gov/).

Several Landsat scenes were obtained from path 171, row 30, centered on the main Caucasus ridge and covering the conical ice cap on the highest mountain peak, Elbrus (5642 m;). A false-colour composite of TM bands 5, 4 and 3 image composed with ADOBE photoshop, from 2011.08.11 has been used for drawing the surface of Chaalat, Adish and Tviber glaciers. The 5, 4, 3 false-color composite image proved accurate in determining glacier termini because: (a) proglacial meltwater streams emanating from the snout were clearly visible as bright blue surrounded by pink/purple unvegetated debris, and (b) a drop in elevation at the terminus of a steep snout often cast an obvious shadow that appears darker than the surroundings.

The same has been done with older sources such the Soviet map that represents the glaciers status in 1965. The older cartographic source available is the Freshfield map from 1889 that has been properly georeferenced. The maximum glacier extinction during the LIA in South Caucasus is probably happened around 1810 (Gobejishvili, personal communication). This limit is visible in the field thanks to the presence of well preserved moraines. Garmin e-trex vista GPS surveys permitted the estimation of the LIA’s maximum glaciers extension.



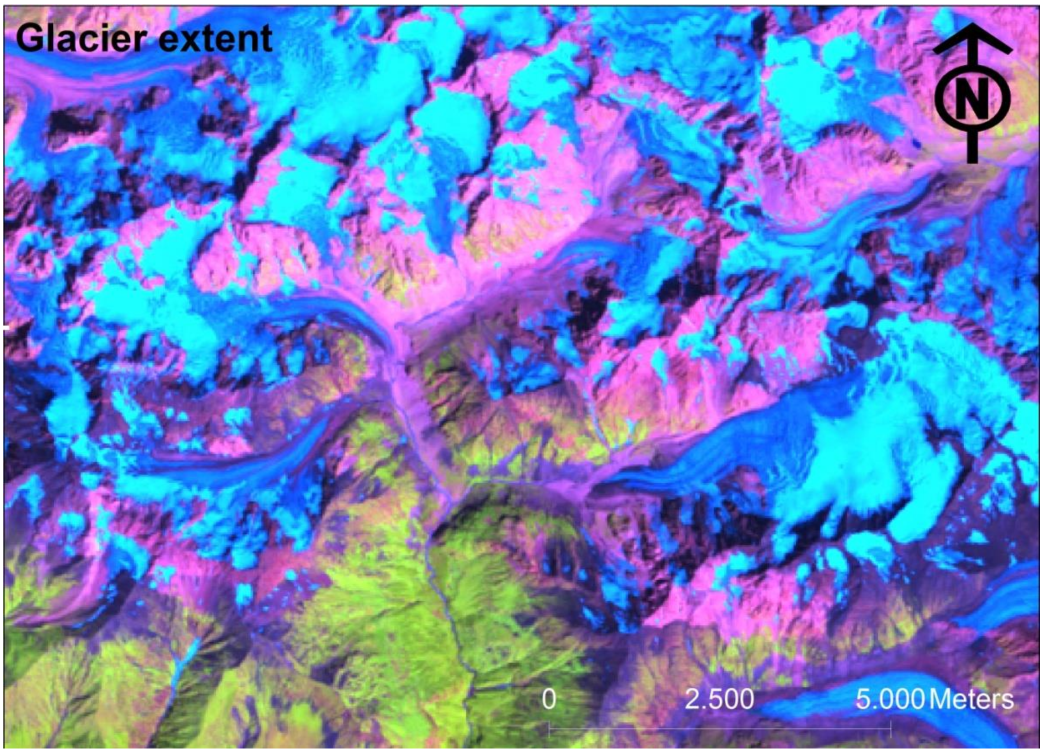


Fig. 7 and 8: the Freshfield map based on the geographical surveys from 1889 (above) and the false-color composite of TM bands 5,4,3 of the Tviber glacier. Image from 2011.08.11, filtered with ADOBE Photoshop.

The terminus position of the 3 glaciers was reconstructed, as well as from sources already considered, even by Google Earth images from 2003 and 2004 and TM images from 2000. The strong retreat rate measured was way larger than the pixel size of the images and permitted consistent values of retreat in the different time intervals.

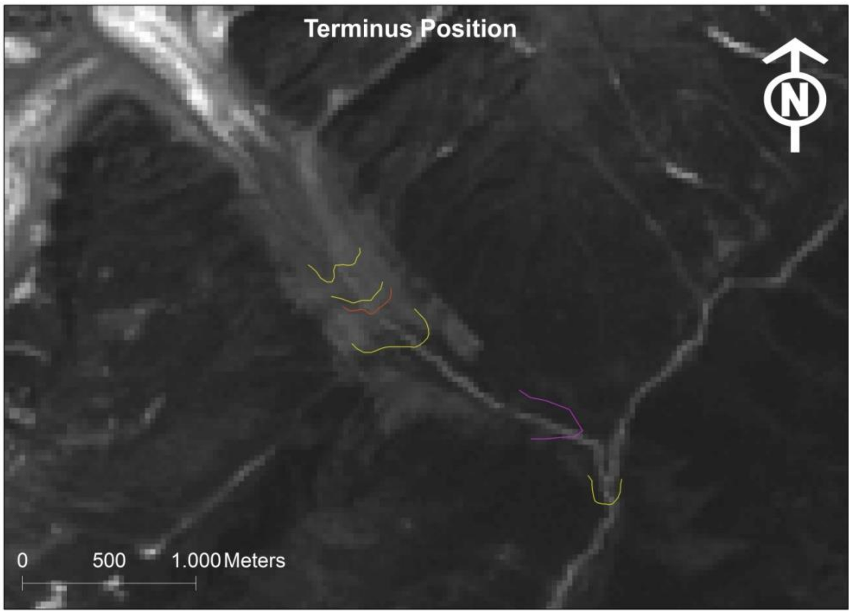


Fig. 9: Terminus position of the Chaalat glacier from the LIA maximum (right) to the 2011 GPS and Landsat survey (left). In between, from right to left is visible the position in 1889 (Freshfield map), 1965 (Soviet map), 2000 (Landsat TM image) and 2003 (Google Earth image).

3 Results

From the LIA to the present the surface of the 3 glacier considered showed strong retreat. Every single interval reconstructed for every glacier showed a surface reduction. It's still possible that there were short periods of expansion lost in the analysis because of the large span of the intervals considered. From LIA to the present, Tviber glacier, the largest glacier in Caucasus until 1965, showed the strongest surface contraction (- 16,4 km² -34,9%) and the strongest terminus linear retreat (- 3967 m, 42% of the maximum length along the main flow line)

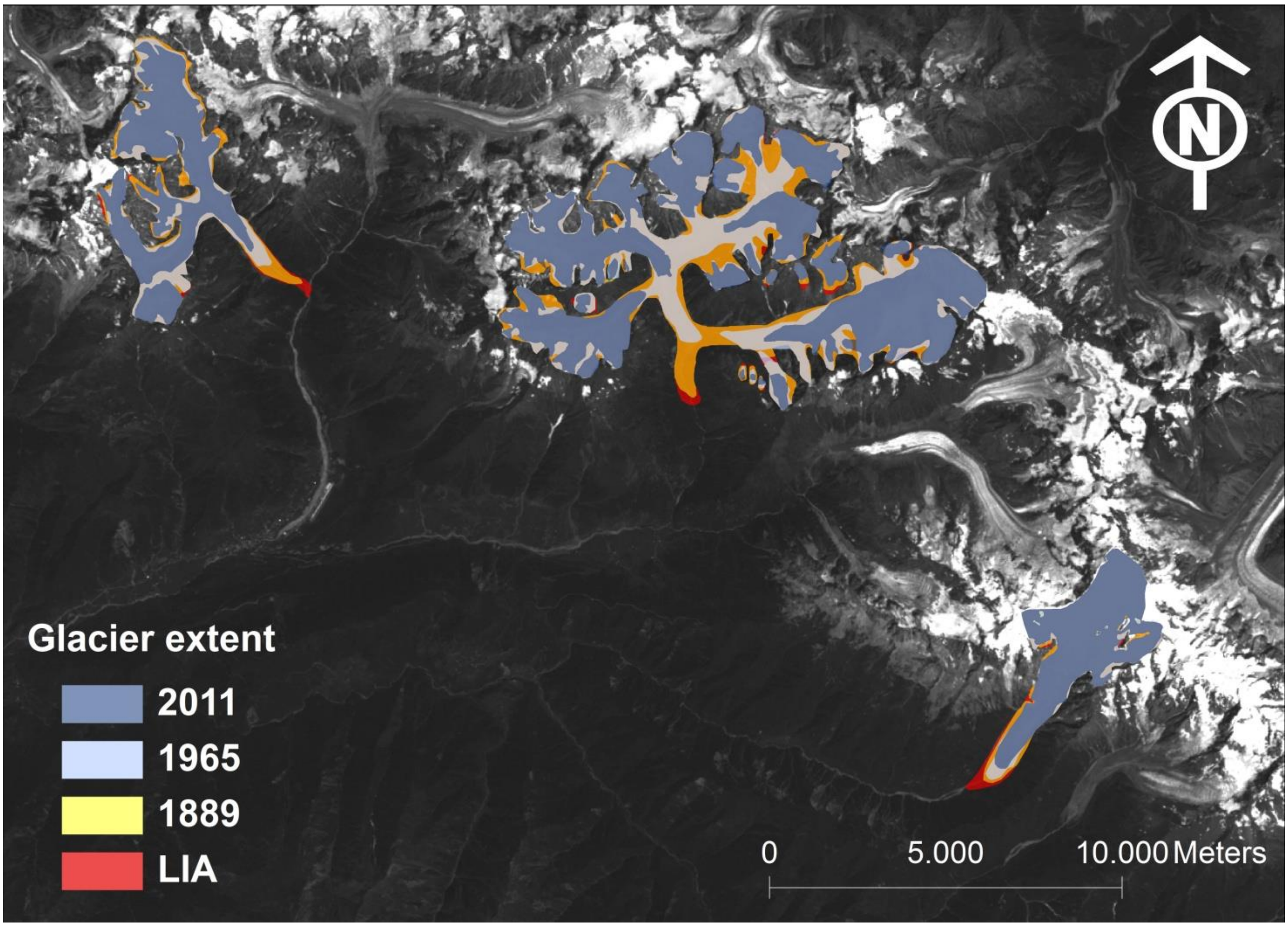


Fig. 9: Glacier extent of Chaalat (left), Tviberi (center) and Adishi (right) from LIA to 2011. On background the Landsat TM image (band 1) from 2011.08.11.

3.1 Chaalat glacier

Fig. 10: Chaalat Glacier in 1889 (V. Sella – fondazione V. Sella) and 2011 (F. Ventura – Macromicro).

Chaalat glacier is historically the one with the lowest terminus elevation (1861 m a.s.l.) in Southern Caucasus. It’s mainly fed by avalanches and it’s SE sided. The glacier area went from 16,2 km² at the LIA maximum extent (1810) to 15,9 km² in 1889, than down to 14,4 km² in 1965 to 11,8 km² in 2011.

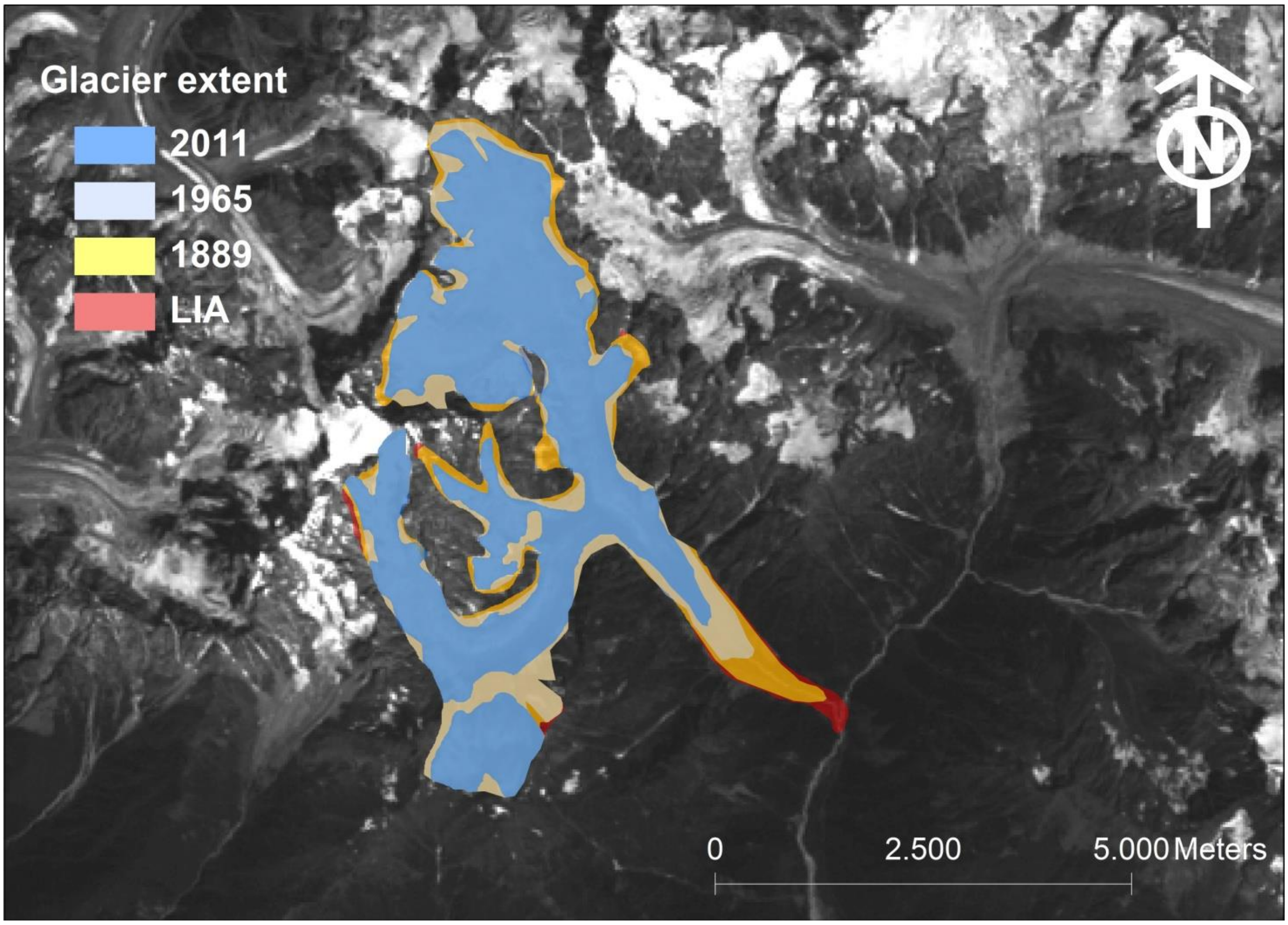


Fig. 11: Glacier extent of Chaalat during the LIA, 1889, 1965 and 2011. On background the Landsat TM image (band 1) from 2011.08.11.

As shown in fig. 12 the retreat rate is gradually increasing in time. More than half of the percentage surface loss from LIA happened between 1965 and 2011. The linear terminus retreat reached 2152 m from LIA to the present (fig. 9 and tab.1). The mean annual retreat is increasing during the last years (- 32,4 m/yr from 2003 to 2011).

interval	Terminus variation (m)	mean annual variation (m/yr)
LIA (1810) - 1889	-461	-6,7
1889 - 1965	-1041	-13,7
1965 - 2000	-335	-9,6
2000 - 2003	-56	-14,0
2003 - 2011	-259	-32,4
Total and average	**-2152**	**- 10,7**

Tab 1. LIA data: field surveys, 1889: Freshfield map, 1965: soviet map, 2000: Landsat TM image, 2003: Google Earth image, 2011: Landsat TM image.

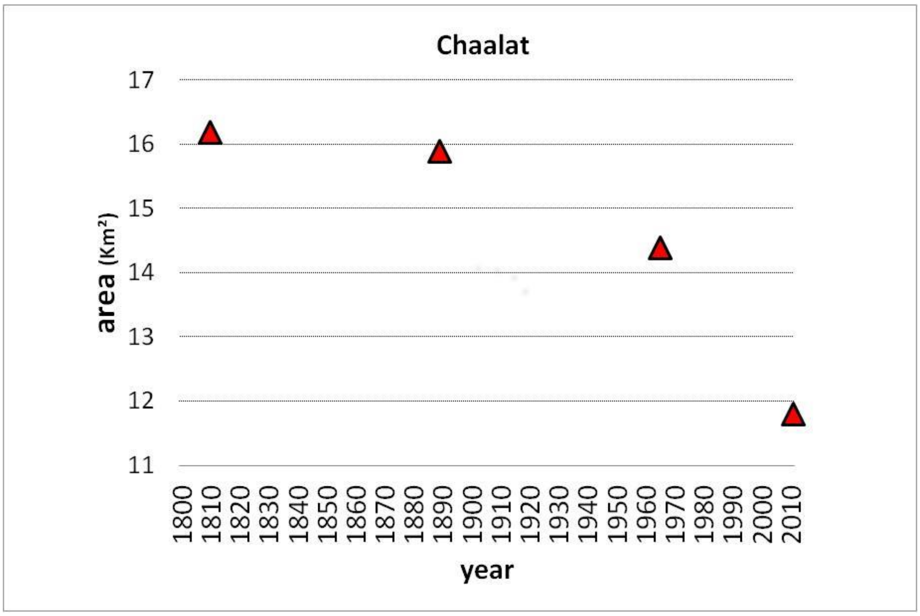


Fig. 11: Chaalat glacier area from 1810 to 2011

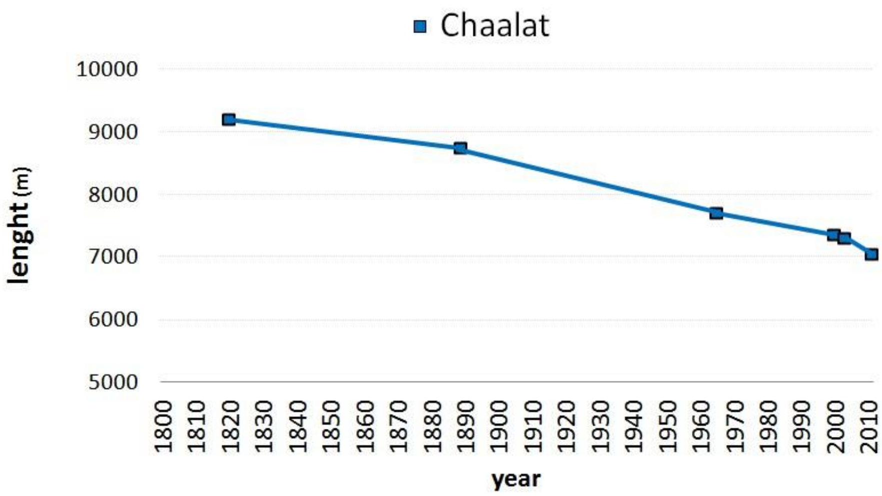


Fig. 12: Chaalat glacier terminus variation from 1810 to 2011

3.2 Tviber glacier

Fig. 13: Tviber Glacier in 1884 (Mor Von Dechy – Royal Geographical Society) and 2011 (F. Ventura – Macromicro).

Tviber Glacier was a large and complicated valley glacier. During the last century the progressive retreat caused the disaggregation of the main glacier body in 15 smaller glaciers. It's mainly fed by avalanches and it's S sided. The glacier area (main body and disaggregated glaciers) went from 47,5 km^2 at the LIA maximum extent (1810) to 47,1 km^2 in 1889, than down to 41,6 km^2 in 1965 to 30,9 km^2 in 2011.

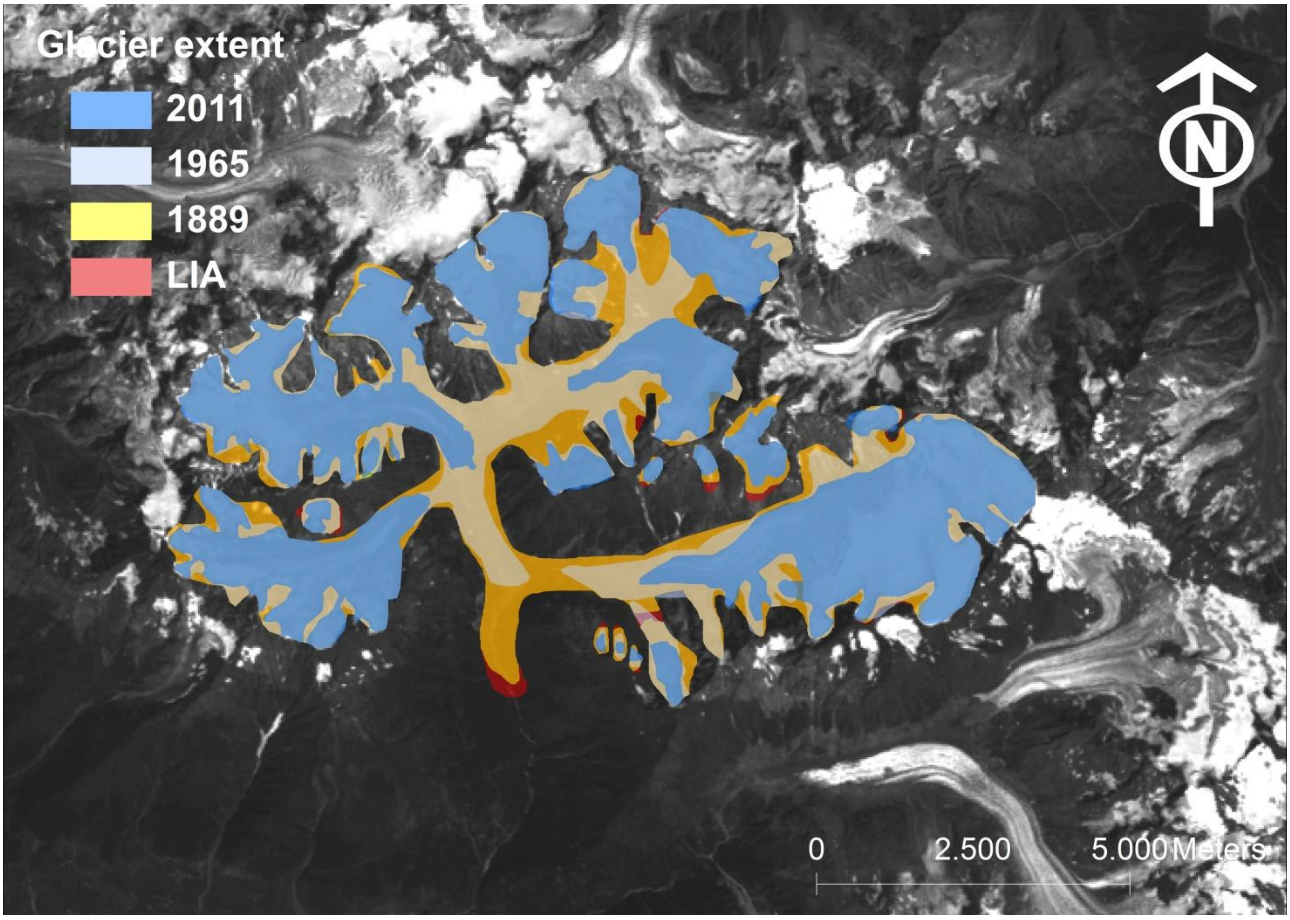


Fig. 14: Glacier extent of Tviber during the LIA, 1889, 1965 and 2011. On background the Landsat TM image (band 1) from 2011.08.11.

As shown in fig. 15 the retreat rate is gradually increasing in time. More than 2/3 of the percentage surface loss from LIA happened between 1965 and 2011. The linear terminus retreat reached 3967 m from LIA to the present (fig. 16 and tab.2). The mean annual retreat is decreasing during the last years due to morphology causes.

interval	Terminus variation (m)	mean annual variation (m/yr)
LIA (1810) - 1889	-183	-2,7
1889 - 1965	-1682	-21,3
1965 - 2000	-1860	-58,1
2000 - 2003	-97	-24,3
2003 - 2011	-145	-18,1
Total and average	**-3967**	**- 19,7**

Tab 2. LIA data: field surveys, 1889: Freshfield map, 1965: soviet map, 2000: Landsat TM image, 2003: Google Earth image, 2011: Landsat TM image.

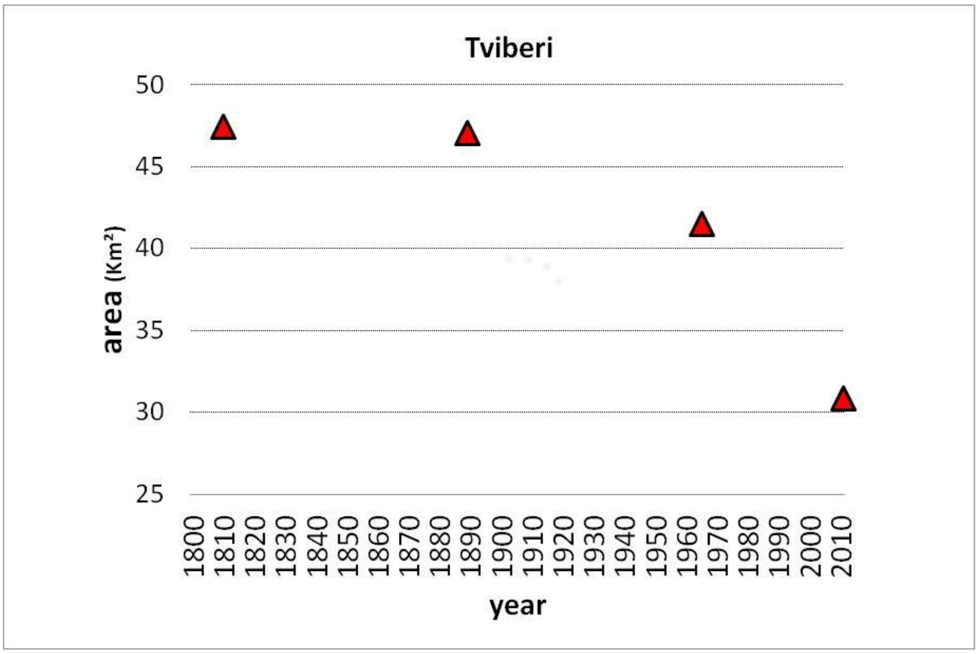


Fig. 15: Tviber glacier area from 1810 to 2011

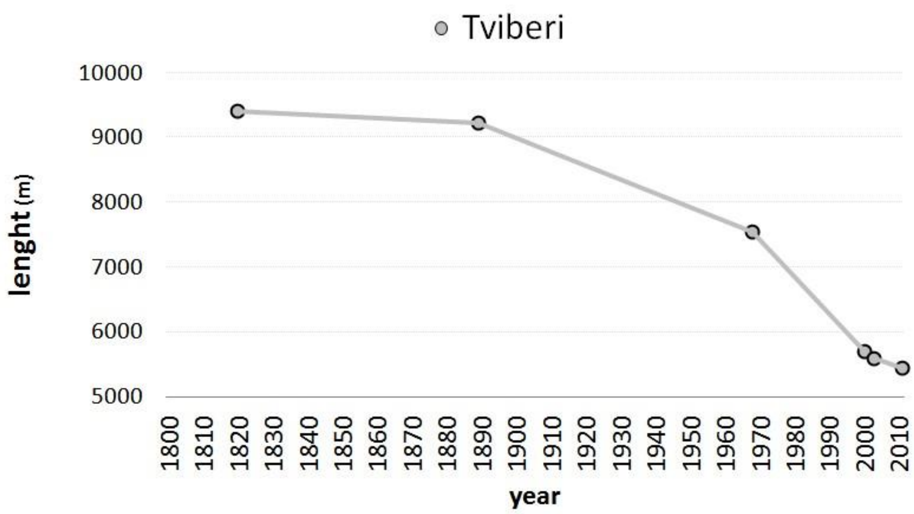


Fig. 16: Tviber glacier terminus variation from 1810 to 2011

3.3 Adish glacier

Fig. 17: Adish Glacier in 1889 (V. Sella – fondazione Sella) and 2011 (F. Ventura – Macromicro).

Adish Glacier is the smaller glacier out of the 3. Besides his surface, the behavior of the glacier during the last 2 centuries is interesting. The surface retreat between LIA (1810) and 1889 was limited (0,3 km²) but proportionally higher than Tviber and Chaalat. From 1889 the retreat rate accelerated, but considerably slower than the other 2. At 2011 the total surface decrease from LIA is 1,5 km² (- 13%). One of the causes of such a behavior can be the extremely high mean elevation of the accumulation basins, 900-1000 m higher than the others. The glacier is mainly fed by direct and wind drifted snow and it's SW sided. The glacier area (main body and disaggregated glaciers) went from 11,3 km² at the LIA maximum extent (1810) to 11,0 km² in 1889, than down to 10,4 km² in 1965 to 9,8 km² in 2011.

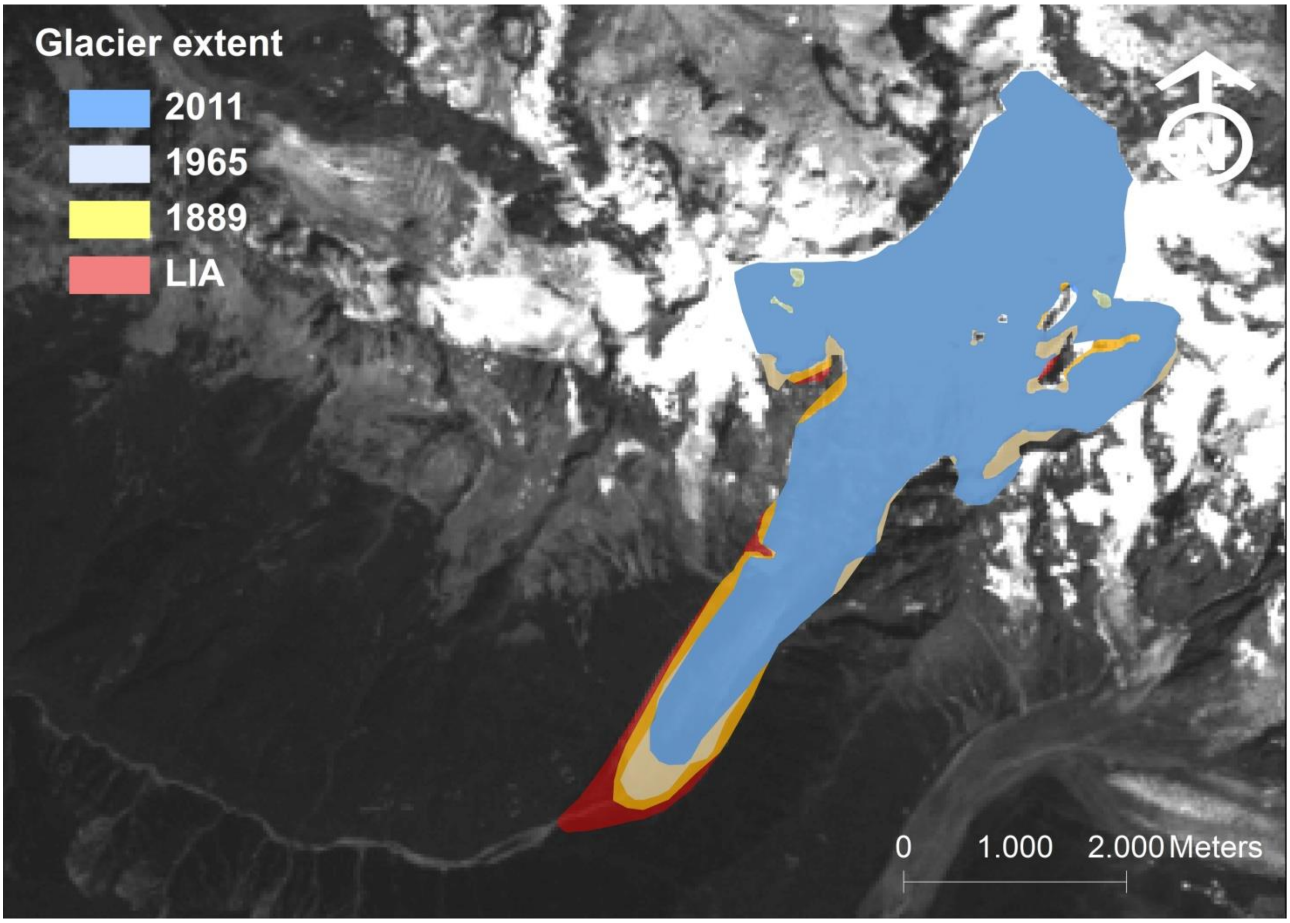


Fig. 18: Glacier extent of Adish during the LIA, 1889, 1965 and 2011. On background the Landsat TM image (band 1) from 2011.08.11.

As shown in fig. 19 the retreat rate is slowly increasing in time. The linear terminus retreat reached 1145 m from LIA to the present (fig. 20 and tab.3). The mean annual retreat between 2000 and 2011 is double compared to the interval 1965-2000.

interval	Terminus variation (m)	mean annual variation (m/yr)
LIA (1810) - 1889	-583	-8,4
1889 - 1965	-131	-1,7
1965 - 2000	-265	-7,6
2000 - 2004	-70	-14,0
2004 - 2011	-96	-13,7
Total and average	**-1145**	**- 5,7**

Tab 3. LIA data: field surveys, 1889: Freshfield map, 1965: soviet map, 2000: Landsat TM image, 2004: Google Earth image, 2011: Landsat TM image.

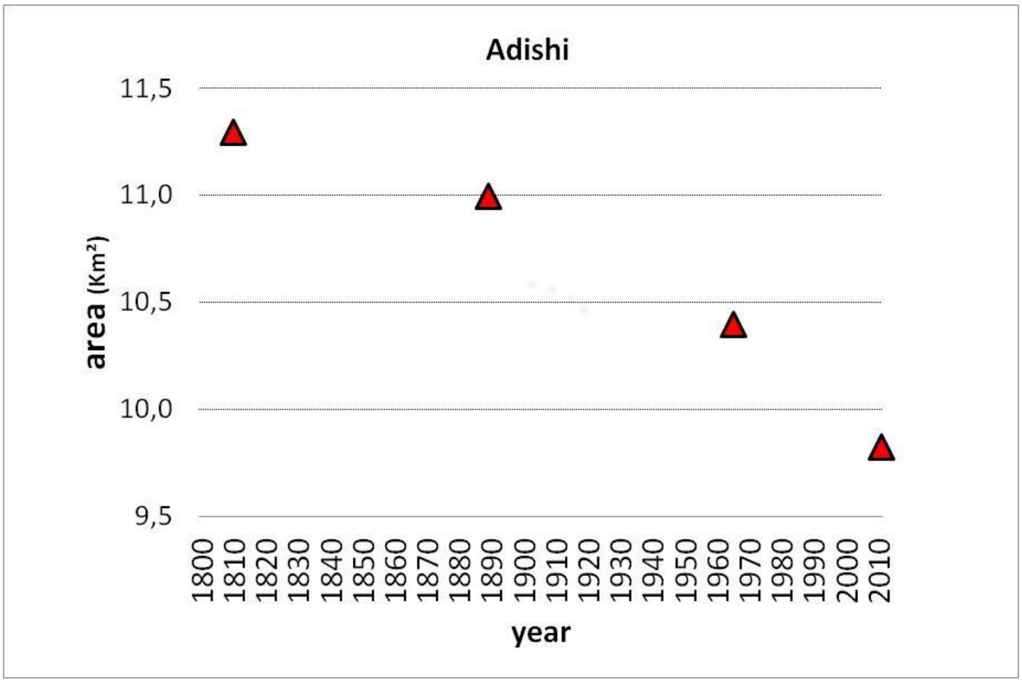


Fig. 19: Adish glacier area from 1810 to 2011

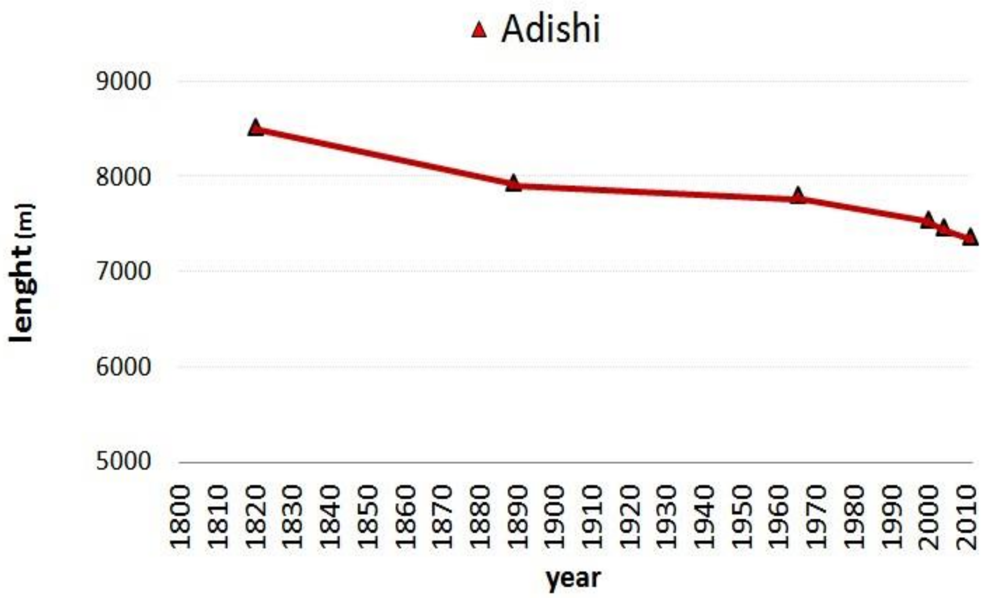


Fig. 20: Adish glacier terminus variation from 1810 to 2011

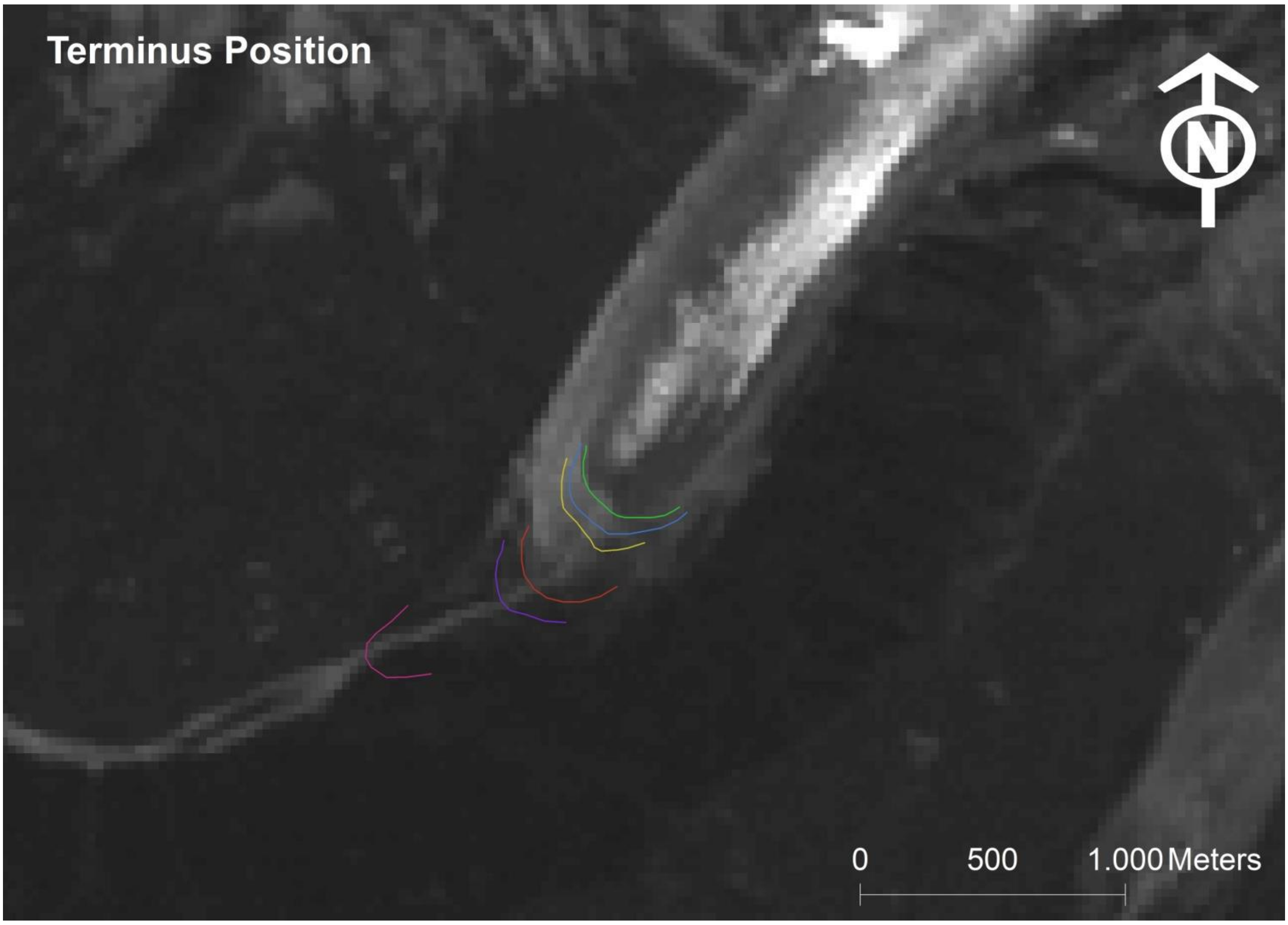


Fig. 21: Terminus position of the Adish glacier from the LIA maximum (down left) to the 2011 GPS and Landsat survey (up left). In between, from left to right is visible the position in 1889 (Freshfield map), 1965 (Soviet map), 2000 (Landsat TM image) and 2004 (Google Earth image).

3.4 Tviber ablation rate experiment

On 8-9 August 8 plastic ablation stakes has been drilled with a hand ice driller in the Tviberi glacier tongue. The stakes were located on a transept transversal to the ice flux along the 2560 m a.s.l. contour line. This particular location permitted to measure the ablation rates of the ice in 24h on strongly different surface conditions and covering. As quite clear in fig. 21, in this part of the glacier are present different debris lithologies with different thickness. The experiment was limited to 24 hour because of logistic problems. 2 stakes (L3 and R6) has been read on 27 August.

Fig. 22: Location of the 8 ablation stakes on the Tviber glacier tongue (R. Scotti)

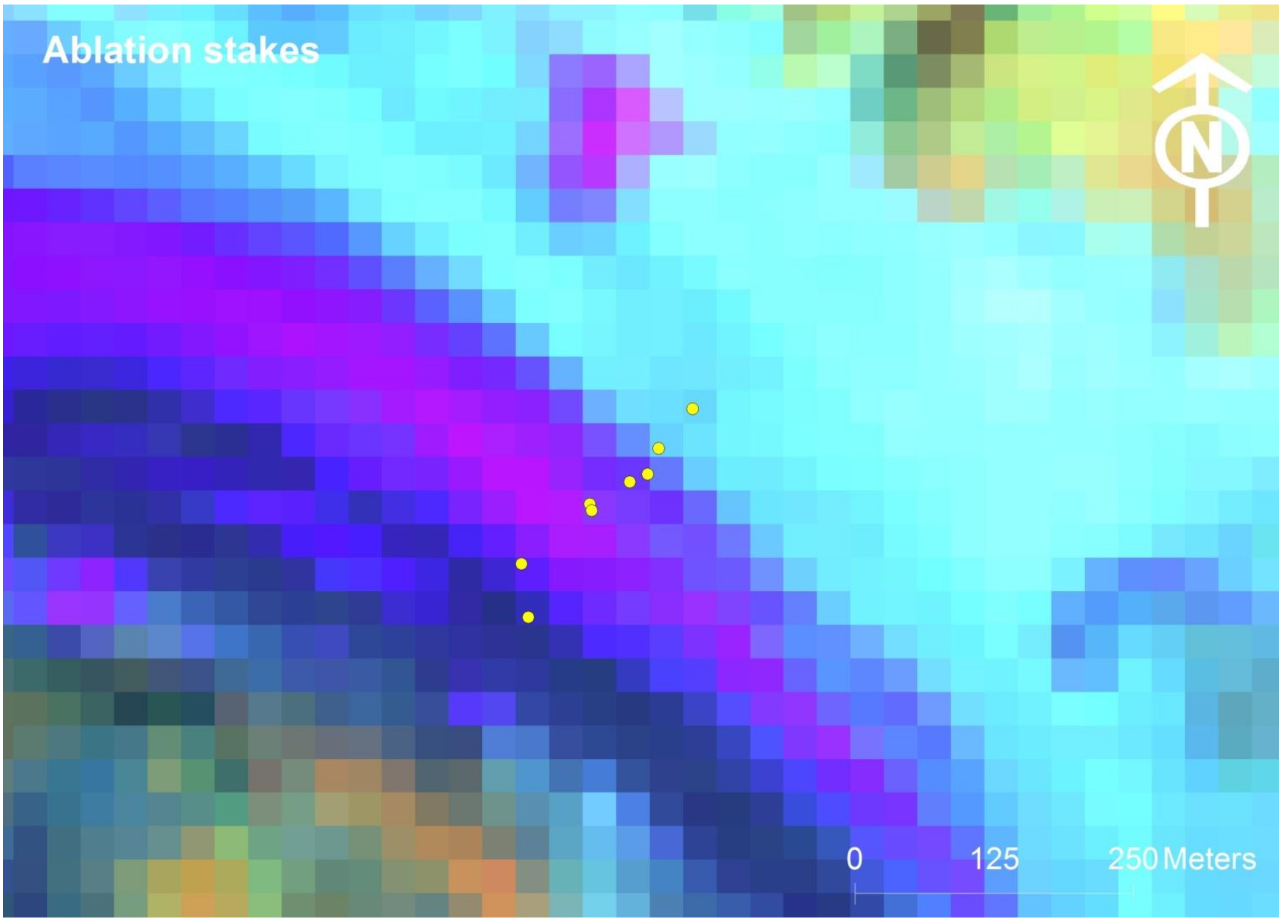


Fig. 23: Location of the 8 ablation stakes on the Tviber glacier tongue. The map is the false color composed TM map from august 11 (just 2 days after the experiment). It's clear the difference in reflectance between the R6 stake (on the the extreme left) that's on black blade shaped clasts to the L3 in the extreme right, on granite deep debris. In the middle the stakes on more or less clean ice.

WEATHER: mixed. On 8th August: sunny morning, with light cloud in early afternoon when stakes drilled. From mid-afternoon increasingly heavy cloud, and complete cover by 15:30. Over night thunderstorms with torrential rain. On 9th August, from sunrise to time of second reading, sunny, occasional small clouds. Katabatic 'glacier' wind involving lower 4-5 m of air over the ice, most of daytime.

STAKES: sites and conditions (L, R = orographic left/right from Stake 1)

Stake 1			
Location	mid-glacier, slight SE slope		
Coordinates (WGS84)	38 T	0326081	4776507
Elevation (m a.s.l.)	2565		
Surface conditions	clean ice, crusty surface 'weathering' layer, scattered fine dust		
Albedo in clear sky (W/sqm)	incoming (225); reflected (56) ** ? setting 2		
Picture **2011-08-08**			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 12:00	-	44	-	-
	09/08 12:00	-	52	8	0.33

Stake L2					
Location	mid-glacier, about 15m from St.1., 4º. SSE slope				
Coordinates (WGS84)	38 T	0326090	4776530		
Elevation (m a.s.l.)	2566				
Surface conditions	dirty ice, near-complete film, wet, light brown mud, fine sand and silt grades				
Albedo in clear sky (W/sqm)	incoming (220); reflected (28) ** ? setting 2				
Picture 2011-08-08					
Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 12:12	-	50	-	-
	09/08 12:12	-	60	10	0.42

Stake L3			
Location	glacier left flank, on major medial moraine		
Coordinates (WGS84)	38 T	0326121	4776566
Elevation (m a.s.l.)	2578		
Surface conditions	irregular surface of broad moraine top; coarse supraglacial debris, many boulders 25-75 cm in diameter, continuous cover of cobbles, with finer material beneath. Thickness at stake c.5 cm in slight depression, where 2-3 cm water when debris removed. Average thickness may be 10 cm		
Lithology	mixed, but mainly light grey, or red-stained granitic material		
Albedo in clear sky (W/sqm)	incoming (218); reflected (32) ** ? setting 2 Individual flat surface of clean, granitic boulder (39)		
Picture **2011-08-08**			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 12:40	48	53	-	-
	09/08 12:30	45	56	3	0.13
	27/08	113	120	64	3.6 cm/day

Stake R2			
Location	mid-glacier, small medial moraine		
Coordinates (WGS84)	38 T	0326065	4776500
Elevation (m a.s.l.)	2567		
Surface conditions	irregular surface relief of c. 10 cm; coarse sand cover of about 1 cm, and openwork angular cobbles, (boulders, but not close to stake)		
Lithology	mainly light grey, granitic material		
Albedo in clear sky (W/sqm)	incoming (220); reflected (28) ** ? setting 2		
Picture **2011-08-08**			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 12:21	68	69	-	-
	09/08 12:25	75.5	76.5	7.5	0.31

Stake R3			
Location	mid-glacier, in widest white ice stream on surface of one of the raised, longitudinal bands raised above surrounding ice about 50-80 cm, slope c 5º to S		
Coordinates (WGS84)	38 T	0326030	4776479
Elevation (m a.s.l.)	2566		
Surface conditions	band of cleanest ice, irregular surface relief of 6-8 cm.		
Albedo (W/sqm)	Albedo measurement on cloudy period, 08/08, 13:50 hr, Incoming (56 = 280 Watts per sq. m.), Reflected (18.5 = 92.5 Watts per sq. m.) = 3.03 NB: regular = 200 setting.		
Picture **2011-08-08**			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 13.21	-	20 + 13 / 2 = 17.5	-	-
	09/08 13:08	-	24 + 21 / 2 = 22.5	5	0.21

Stake R4			
Location	mid-ice 10 m from R3 with similar surrounding		
Coordinates (WGS84)	38 T	0326027	4776489
Elevation (m a.s.l.)	2568		
Surface conditions	smooth, dense ice in bed of small, on-ice stream 2-4 cm deep, (no 'weathering layer')		
Albedo (W/sqm)	N.D.		
Picture **2011-08-08**			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 13:50	-	30.5	-	-
	09/08 13:45	-	35.5	5	0.21

Stake R5			
Location	on left flank of glacier, at base of pronounced medial moraine		
Coordinates (WGS84)	38 T	0325967	4776427
Elevation (m a.s.l.)	2576		
Surface conditions	thin, irregular cover (>1 cm) of black, platy debris of granule to coarse sand grades, flat surface sloping appr. 6º to SSE		
Albedo (W/sqm)	incoming (218); reflected (17) ** ? setting 2		
Lithology	distinctive black, sometimes red stained, slate with thin platy clasts		
Picture 2011-08-08			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 14:14	40.0	40.5	-	-
	09/08 13:45	50.5	51.0	11.5	0.49

Stake R6			
Location	on slightly flattened top of distinctive, 'black' medial moraine of right flank		
Coordinates (WGS84)	38 T	0325973	4776379
Elevation (m a.s.l.)	2578		
Surface conditions	slight depression in relatively smooth surface, 2-5 cm of blackish, platey and blade shaped clasts mainly 3-20 cm in diameter and 0.5 -3 cm thick		
Albedo (W/sqm)	incoming (219); reflected (17) ** ? setting 2		
Lithology	distinctive black, sometimes red stained, slate		
Picture 2011-08-08			

Ablation rate	Date/Time	TTD (cm)	TTI (cm)	Ablation (cm)	Rate (cm/h)
	08/08 14.24	40	42	-	-
	09/08 13:55	46	48	6	0.26
	27/08	145	147	99	5.5 cm/day

The ablation rates recorded are in the range between 0,13 cm/h (stake R3) with a 5 cm debris cover to 0,49 cm/h of the stake R5 (0,5 cm of debris cover). The relation between debris thickness and ablation rate is shown in fig. 24. The thickness beneath which maximum melt occurs (0,5 cm) and the thickness at which melt becomes inhibited compared to that of clean ice (around 3,3 cm) is similar to the literature values (fig. 25)

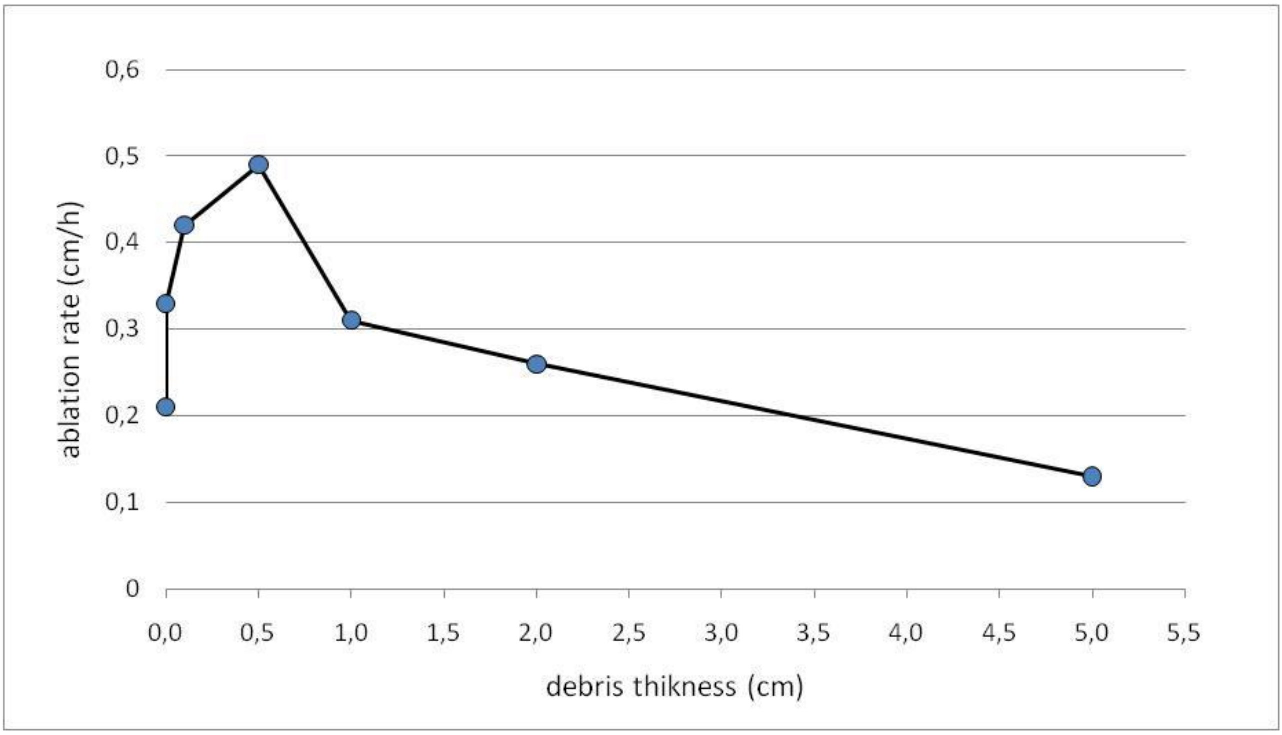


Fig. 24: relationship between debris thickness and ice ablation rate between 8 and 9th August 2011 on Tviber glacier

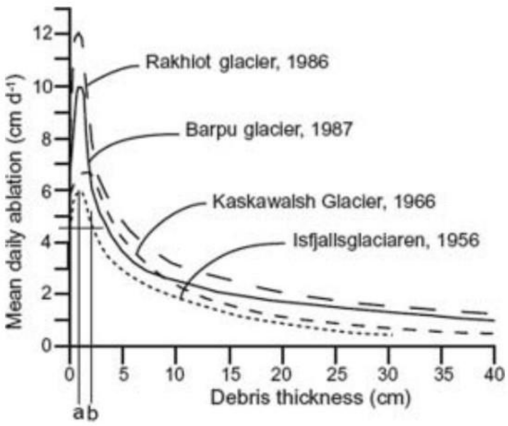


Fig. 25. Examples of empirical measurements of the relationship between debris thickness and ice ablation rate on sample glaciers (redrawn from Mattson and others 1993): Rakhiot glacier, Punjab Himalaya; Barpu glacier, Karakoram Himalaya, Pakistan; Kaskawalsh Glacier, Yukon, Canada; and Isfjallsglaciaren, Sweden. Notethe variation in (a) the thickness beneath which maximum melt occurs and (b) the thickness at which melt becomes inhibited compared to that of clean ice on different glaciers (indicated for Isfjallsglaciaren). (In Nicholson and Benn, 2006)

4 Discussion

Chaalat, Tviber and Adish glaciers are A raw look at the areal variations of the surrounding glaciers on the sources used in this study highlights how these 3 glaciers are a reliable sample for the knowledge of the recent variations in Upper Enguri river basin. Nevertheless the difference in behavior between those 3 glaciers is quite high. For example, from the LIA to the present, the area decrease in percentage of the Tviber glacier is 3 times higher than the one of the Adish glacier.

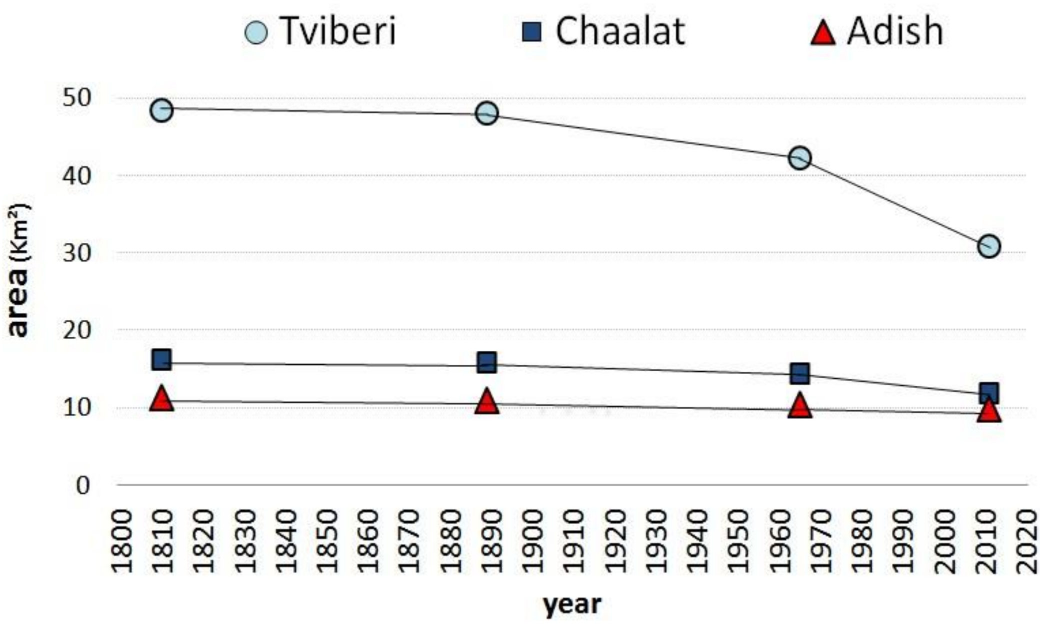


Fig. 26. Area of the 3 glaciers from 1810 to 2011.

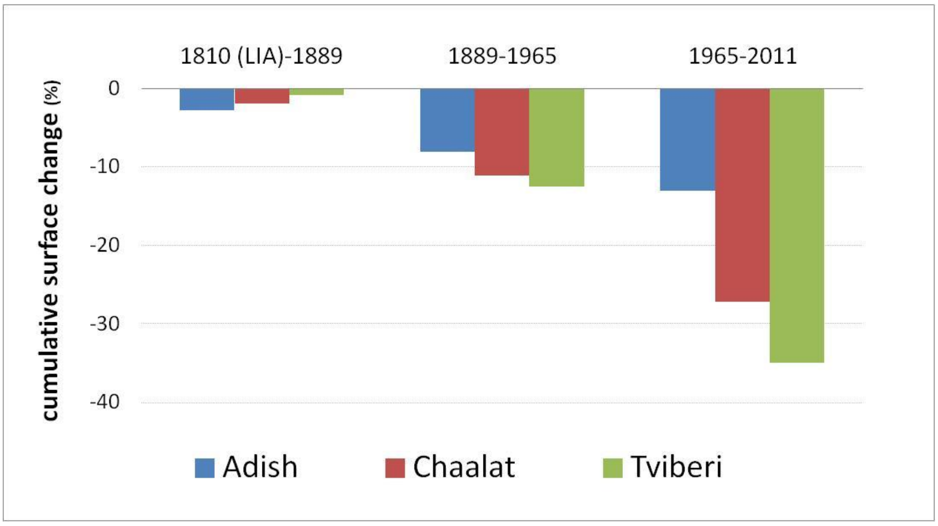


Fig. 27. Cumulative surface changes (%) from the LIA maximum. The percentage retreat of the Tviber glacier is 3 times the retreat of the Adish glacier.

One of the most interesting and importance result from this study is the acceleration in surface dilapidation shown in the last interval (1965-2011) compared to the previous intervals. In this interval Tviber glacier has lost surface 3,2 times faster than in the previous interval, and close to 50 times faster than in the XIX century. The other two glaciers are showing the same behavior (fig. 28)

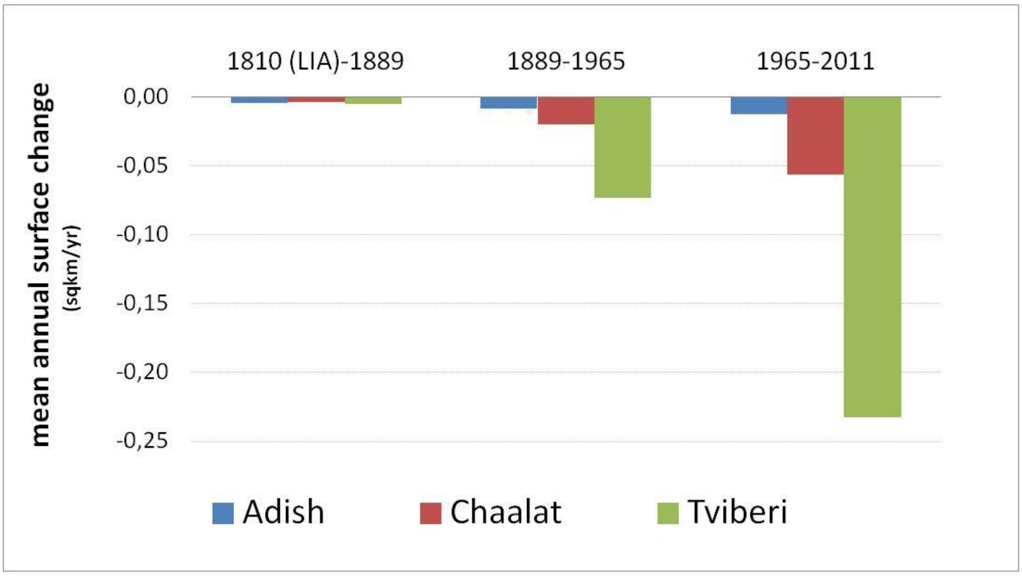


Fig. 28. Mean annual surface change in km²/yr

One of the possible explanation of the difference in surface change between the 3 glaciers can be found in the elevation profile of the glaciers. As highlighted in fig. 29, there is an inverse relation between the terminus retreat (and surface retreat) and the accumulation basins mean elevation. This parameter is linked with the elevation of the highest top feeding the glacier. The Adish glacier is fed by 2 accumulation basins at the mean elevation of 4313 m a.s.l., respectively 900 and 1000 m higher than Chaalat and Tviber. Such high elevation is probably still untouched by the climate change.

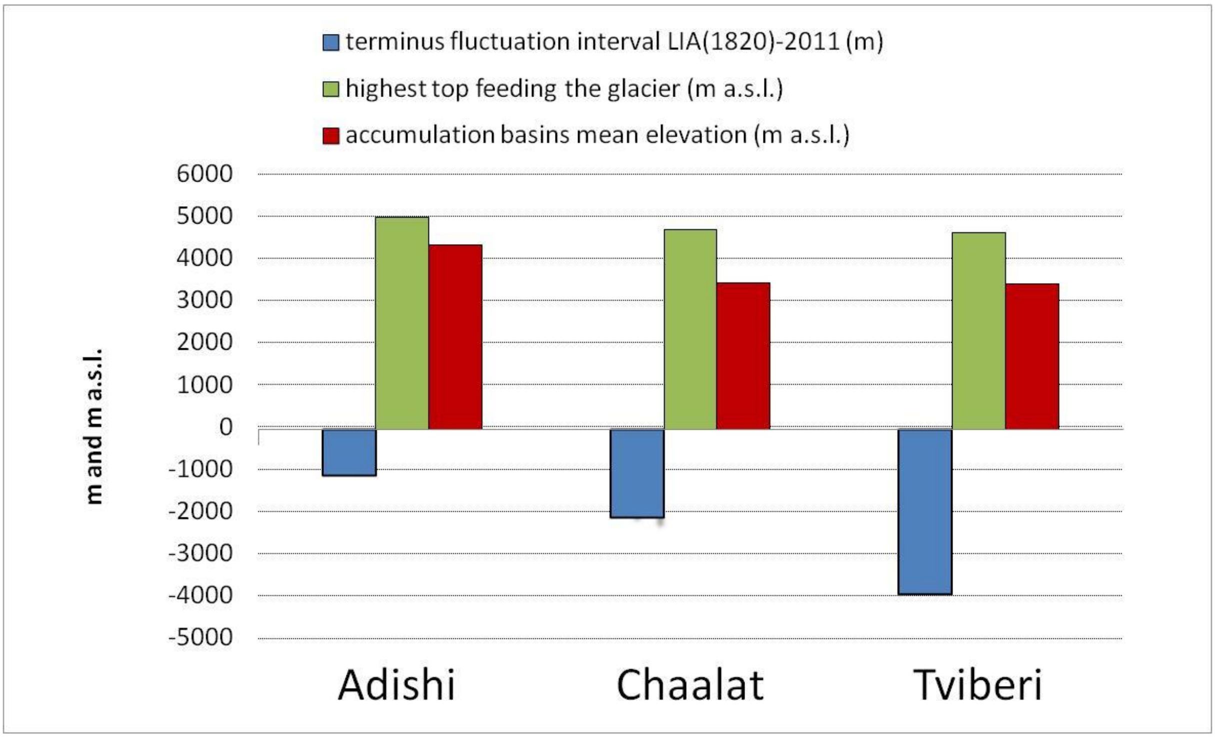


Fig. 29. Relation between the terminus fluctuation in the interval LIA – 2011 and the elevation profile of the accumulation basins of the glacier and the highest top feeding the glacier.

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