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Glaciers and the Polar Environment

Edited by Masaki Kanao,
Danilo Godone and Niccolò Dematteis

Chapter 6

Risks of Glaciers Lakes Outburst Flood along China Pakistan Economic Corridor

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Abstract

The China-Pakistan Economic Corridor (CPEC) passes through the Hunza River basin of Pakistan. The current study investigates the creation and effects of end moraine, supra-glacial, and barrier lakes by field visits and remote sensing techniques along the CPEC in the Hunza River basin. The surging and moraine type glaciers are considered the most dangerous type of glaciers that cause Glacial Lake Outburst Floods (GLOFs) in the study basin. It can be concluded from the 40 years observations of Karakoram glaciers that surge-type and non-surge-type glaciers are not significantly different with respect to mass change. The recurrent surging of Khurdopin Glacier resulted in the creation of Khurdopin Glacial Lake in the Shimshal valley of the Hunza River basin. Such glacial lakes offer main sources of freshwater; however, when their dams are suddenly breached and water drained, catastrophic GLOFs appear and pose a great threat to people and infrastructure in downstream areas. This situation calls for an in-depth study on GLOF risks along the CPEC route and incorporation of GLOF for future policy formulation in the country for the CPEC project so that the government may take serious action for prevention, response to GLOFs, and rehabilitation and reconstruction of the areas.

Keywords: glaciers, GLOF, CPEC, climate change, lakes

1. Introduction

The high altitudes of the China Pakistan Economic Corridor (CPEC) region encompass glaciers as frozen reserves of water which act as an important natural resource by supplying fresh water to millions of people living the mountainous and downstream areas. The water released from the glaciers acts as a perennial source for most of the Himalayan Rivers [1]. The rivers and streams originating from these glaciers not only serve as power generation from hydroelectric power plants but also irrigate the agricultural lands in the command area during summer and also provide water for industrial purposes. Like this, these glaciers control the socio-economic activity in this part of the CPEC region. Therefore, the meltwater from the snow and glaciered region is of high importance for the runoff in the Indus River [2]. There is a lack of exact facts and figures about the exact contribution of flow in the region due to rugged mountains and the limited data availability because there is a highly different precipitation rate due to the settings and steep topography. Similarly, there are extremely different ablation rates due to aspect and variable debris cover on the glaciers. However, an extensive field study was conducted by the Snow and Ice Hydrology Project (SIHP) of Water and Power Development Authority (WAPDA) with the collaboration of Canadian University during the 1980s. It was reported that the maximum precipitation occurs at the elevation of 4500–5100 m.a.s.l. Moreover, Hewitt [3] reported that about 80% of flows in the Upper Indus River derives from the glaciered region above 3500 m.a.s.l. Recently, researchers have tried to assess the spatial distribution of precipitation by inversely inference of precipitation for glacier mass balance [4] snow cover variation [1, 5] using remote sensing data, Geographical Information System (GIS) techniques, and runoff modeling approaches. Adnan et al. [5] reported that the expansion in snow cover in the Hunza River could be attributed to the surge activities in the basin. Many researchers [6–10] have reported the surge events in the region. Studies on glaciers also indicate the slightly reduced mass balance in the region. However, most of the glaciers have gained the mass in the nourishment zone and loss in the ablation zone. These findings suggest the increase in the slopes of the glacier that could cause increased glacier velocities and the probable advance of glaciers in the future. However, in this chapter, we have presented the existence of glaciers and glacial lakes in the Hunza basin through which the CPEC route passes and is a heavily glaciered region. Many GLOF events and surges have been reported in the basin, especially, along the CPEC route. Moreover, glaciers are sensitive indicators of global climate change because they remain sensitive to global temperature conditions as specified by their continuous retreat which has been witnessed in many parts of the world including the Hindu-Kush Karakoram Himalaya (HKH) region especially CPEC route [9, 11]. After the industrial revolution, the rapid glaciers melting and its associated retreating trend left a major concern to the scientists and managers in the region. The substantial glaciers melting not only decrease the rivers discharge in the long run but also bring the high sediment load which causes flash floods in downstream areas and has a direct posture on the life of hydropower projects and socio-economic consequences for the local people and those living in downstream areas.

1.1 Glacial Lake Outburst Floods (GLOFs)

Terminal moraines and glacial lakes have been exposed in these high mountains as a result of surging, substantial melting, and retreating of glaciers. GLOFs have become a matter of concern for social and economic stability in the river valleys because of the rapid addition of meltwater in those glacial lakes adjacent to receding valley glaciers and may lead to sudden breaching of the unstable debris dam. Thus, it is very important to understand the state and fate of these glaciers and lakes as well for long-term development and planning in this region [12, 13].

During the last half-century, a large number of glacial lakes development have been witnessed in the CPEC region, and at the same time, several GLOFs have been reported, especially, in the eastern part of the CPEC region. Probably, remote glacial lakes are under risk and they may impact the downstream inhabitant as a result of GLOFs. These GLOFs may have devastating effects on the population as well as property and infrastructure [14–16].

The understanding that GLOFs can significantly surpass design floods of Hydropower Plant (HPP) under the threat of destruction or complete non-functionality is based on few case studies [17–19] but a clear picture of regional GLOF exposure remains vague. The previous glacial lake inventories to identify future GLOF sources have neglected their impacts on downstream areas [20]. However, hydrodynamic modeling may encounter such kinds of impacts but it requires a detailed analysis of high-resolution Digital Elevation Models (DEMs) and high computation facilities so that simulations of possible outbursts are existing for only a handful of lakes [12, 21, 22]. This research gap has been filled by linking a glacial lake inventory with both flood propagation and a dam-breach model to assess potential flood magnitudes for a sample of operating, planned, and currently built hydropower plant in the CPEC region [23–25].

Regional predictions of peak discharges as a result of GLOFs are difficult because of the unavailability of data on the geometry of glacial lakes and the moraine dams. The current field visit as well as different researchers provided an alternative solution to this problem and use the range of the simulated peak discharges at each HPP as a measure of uncertainty of GLOF exposure. For our flood propagation model, the volume and the resulting distributions of peak discharges for each lake have been used as the initial conditions during the field visit.

2. Hunza River basin

CPEC is in the interest of both the countries China and Pakistan; it will develop connectivity between west China and south China; and it is an integrated part of the "One Belt One Road" initiative policy. The establishments of China and Pakistan have agreed to complete the CPEC route from Kashgar (China) to Gwadar (Pakistan) by the end of 2030. The Chinese government is providing necessary support in terms of finance and logistics to build the infrastructure along the CPEC route. The CPEC is not only important for both the countries but also will prove beneficial for the surrounding countries. This project will strengthen the economic growth of Pakistan and it is the right initiative for both the countries. This corridor is considered a sign of peace, prosperity, and development. Even though this economic corridor is challenging but it will open new horizons of development in the future for both the countries. In the past, the lack of the right decision and insufficient opportunities have always remained a hurdle in the way of Pakistani peoples but CPEC will have transformational impacts on the state and the prosperity Pakistani nationals. The Chinese president Xi's visit in April 2015 and the announcement of $46 billion-plus for various CPEC projects drew the world's attention to this region because new development and growth of the economy will benefit both of the countries under the umbrella of this economic corridor. In the meeting called by the Prime Minister of Pakistan, all political parties have supported the CPEC and project and warmly welcomed the Chinese investment. This project will bring a revolution in the lives of over 3 billion people in this region. It will improve the strategic and economic location of Pakistan through trade and investment and exploration of mineral resources. Alternatively, according to China's perspective, this is a "flagship project" because it provides the shortest route to the Middle East, Africa, and Europe, which will boost up its economy. This corridor is passing through the Northern part of Pakistan.

The northern part of Pakistan is mostly consisting of a mountainous region, which is rich in glaciers and glacial lakes. The source of water in the river is glacier melting and rainfall. The population living downstream is under high risk due to the melting of glaciers and GLOFs [26–28]. International Center for Integrated Mountain Development (ICIMOD's) published an inventory in 2005, which comprised of 2420 glacial lakes in 10 major river basins of Hindukush Karakoram Himalayan Region of Pakistan [29]. The different river basins have glacial lakes such as Gilgit (614), Indus (574), Swat (255) Shingo (238), and Hunza (110). The Gilgit River basin comprised of 614 glacial lakes and 380 lakes out of 614 were identified

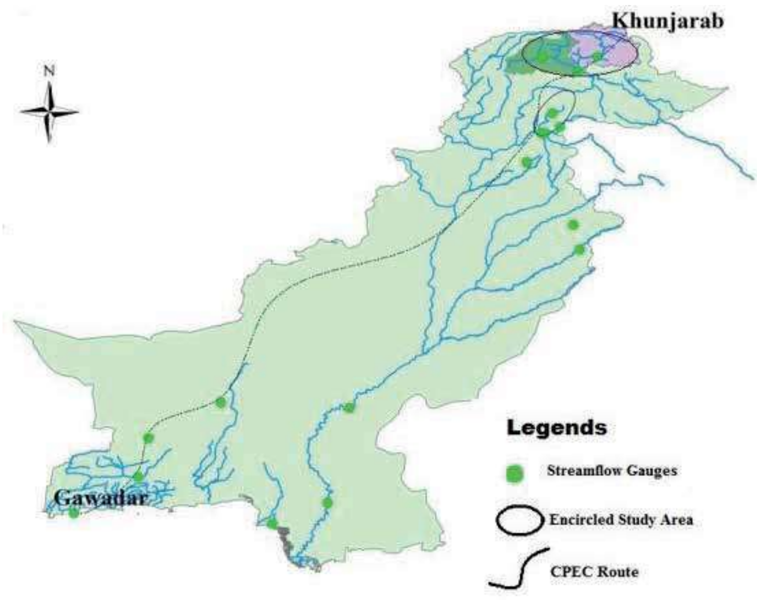

Figure 1.
Study area of China Pakistan economic corridor.

as major lakes, which contribute 62% of the total lakes. These major lakes form 93% of the lake area of the basin. New glacial lakes also formed due to glaciers thinning and retreating of this region. These lakes are categorized according to risk, 52 glacial lakes identified in this region. Passu lake has experienced historical GLOF events, which lie in the Hunza River basin [6]. The location of Passu lake is 38 km away and directed to the East-West of Passu glacier in the HKH region (**Figure 1**). The climate of Hunza is moderate, which have minimum and maximum temperature of 16 and 35.9°C, respectively. The annual average rainfall in this region is 136.2 mm with a minimum (2.1 mm) and maximum (283.2 mm) in November and April, respectively [30].

3. Materials and methods

3.1 Glaciers along CPEC route

The CPEC route passes through the Hunza River basin which is a glaciated region of Gilgit Baltistan. The route starts from China to Pakistan through the Sost border which lies in the Hunza River basin. Approximately, 28% of the Hunza basin area is covered by glaciers, and Passu, Batura, and Ghulkin are some known glaciers that exist along the CPEC route (**Table 1**), which have an established history of GLOF events. The Karakoram Highway and other roads in Shimshal and the Nagar River basins have been damaged many times because of GLOF events from the glaciers.

3.2 Assessment of GLOF using remote sensing data and GIS

Rugged mountain conditions make it difficult to investigate the glacial lakes for the whole region. However, the end moraine and the lakes in the blocked river valleys (e.g., Khurdopin glacial lake) were investigated with physical visits. However, the area's calculations and the causes of surging were made through remote sensing data and GIS

River basins	Glaciers			Glacial lakes		
	no.	Area (km^2)	Ice reserve (km^3)	No.	Area (km^2)	Potential danger
Swat	233	223.55	12.221	255	15.86	2
Chitral	542	1903.67	258.817	187	9.36	1
Gilgit	585	968.1	83.345	614	39.17	8
Hunza	1050	4677.34	808.794	110	3.21	1
Shigar	194	2240.08	581.27	54	1.09	0
Shyok	372	3547.84	891.8	66	2.68	6
Indus	1098	688	46.38	574	26.06	15
Shingo	172	36.91	1.009	238	11.59	5
Astore	588	607.03	47.931	126	5.52	9
Jhelum	384	148.18	6.943	196	11.78	5

Table 1.
Summary of glaciers, glaciers lakes, and potentially dangerous lakes in CPEC region [31].

techniques. The Landsat satellite images for May and June 2017 were downloaded from the website; http://earthexplorer.usgs.gov/ to explore the formation of newly developed lakes due to river blockage caused by the surging of Khurdopin glacier. The formation of the newly developed lakes was identified from the visual interpretation of the images in the ArcGIS tool, whereas Temporal Geodetic mass balance is employed to compute the vertical changes in glaciers by using remote sensing data of that region. The potential GLOF lakes were identified base on the following criteria and physical conditions [24]:

The rise in water level in glacial lakes, which creates the condition to breach the lake.

The lakes form on the glacial surface, which produces the combined effect with a group of lakes. It became potentially dangerous lakes.

The valley lake also becomes the potential GLOF lake due to short distance from mother glaciers tongue and the size of lake also plays an important role.

A lake several times breaches and damages the downstream. These types of lakes filled again and breach again.

The physical conditions of the surrounding of the lake also play a vital role to identify the potential dangerous glacial lake.

There is still no standard to identify the potential glacial lakes. The above mention criteria and condition decide the potential dangerous glacial lakes.

3.3 Field investigations for GLOF events

Remote sensing and field investigations are two basic methodologies used to assess the GLOF events (**Table 2**) and their credible effects. The number of glacial lakes, their areas, and geodetic mass balance for surging glaciers have been estimated through remote sensing techniques; whereas, field investigations help to assess the severity of the GLOF event. Moreover, the possible disaster from the potential hazard lake can be investigated through field investigations in terms of barrier strength, discharge conditions, and depth of the lake.

Pakistan Snow and Ice Hydrology Project (PSIHP) of WAPDA in collaboration with a Canadian University studied the Khurdopin glacier for precipitation input. They also did field visit of Batura glacier and Passu lake through the collaboration of Joint Venture of National Science Foundation of China, under the umbrella of the institute of international Rivers and Eco-security, Yunnan University,

Year	Event date	Glacier	River	Influencing factors
1973	—	Batura	Hunza	—
1974	—	Batura	Hunza	—
1977	—	Balt Bare	Hunza	—
1978	September	Darkot/Barados	Gilgit	—
1994	July	Sosot/Gupis lake	Gilgit	—
1999	6 August	Khalti/Gupis	Gilgit	Moonsoon rainfall
2000	10 June	Shimshal	Hunza	High temperature
2000	27 July	Kand/Hushe	Indus	Moonsoon rainfall
2005	July	Sosot/Gupis lake	Gilgit	
2007	5 April	Ghulkin	Hunza	Western disturbance
2008	6 January	Passu	Hunza	Western disturbance
2008	2 April	Ghulkin	Hunza	Western disturbance
2008	22 May	Ghulkin	Hunza	Persistent rainfall
2008	24 May	Ghulkin	Hunza	Persistent rainfall
2008	14/15 June	Ghulkin	Hunza	Heat wave
2009	26 March	Ghulkin	Hunza	Western disturbance
2018	17 July	Barsuwat glacier	Immit	Heat wave
2019	23 June	Shishper	Hunza	High temperature
2020	29 May	Shishper	Hunza	High temperature

Table 2.
History of major GLOF events in CPEC region.

Kunming, China, and ICIMOD. The remote sensing and field observations analysis of Khurdopin glacier provides up to date evidence about glacier surge and its possible impacts on the downstream populations because of the newly developed lake.

4. Results and discussion

4.1 GLOF events in Hunza basin

Glacial lakes formation depends on the type of glacier, its slope, and geological settings. For example, a supraglacial lake creates on the surface of glaciers when its slope is less than 2%. Similarly, surging glaciers block the river valley and cause the formation of the lake. Moreover, moraine-dammed lakes develop due to the advancement or recession of valley glaciers. Overall, these GLOF events depend on the physical and topographical conditions and the nature of damming materials. The severity of damages increases as the elevation and the volume of the glacial lakes increases. The type of moraine-dammed and the surging glaciers are the most dangerous types that block the valleys and cause GLOF events in the basin. In this regard, the type of GLOF event for the glaciers in the Hunza Basin is also not the same for example; Passu glacier caused damage due to outbursts of the end-moraine dammed lake, supra-glacial lake outburst occurred from Ghulkin and Hispar glaciers, valley blocked by Khurdopin glacier. GLOF from these glaciers bring rocks and the mudflows in the glacial streams, for example, significant mudflows released from Batura glacier.

4.2 GLOF events associated with surging of glaciers

The surging activities of the glaciers in the Hunza Basin have also been interpreted by earlier studies [14, 32, 33] from a stable or slightly increasing trend of snow cover for the Hunza River basin [1, 25]. It has been reported recurrent surges for several glaciers of the Hunza Basin [6]. For example, Bolch et al. [20] and Quincy and Luckman [34] have comprehensively reported the surge history of Khurdopin glacier. The glaciated area of Khurdopin glacier is 115 km^2 which is situated in Shimshal River, a tributary of the Hunza River. The first surge has been reported in 1979 and the second surge event occurred in 1999 and both surge events occurred in the summer season. The latest surge was observed during the summer season of 2017 [35]. These events suggest the return period of the surge event for Khurdopin glacier is about 20 years. No significant change has been observed in the debris cover Hispar and Shimshal glaciers of the Hunza basin for the period of 1977–2014 [36]. It was determined that this might be due to balanced glacier budgets during this period. Type of glaciers and their areas are given in **Table 1**.

The surging of Khurdopin glacier has resulted in the formation of the medium-sized ice-dammed lake at an elevation of 3454 m a.s.l and it lies at latitude-longitude of 36°21′007″ N and 75°27′51.2″ in the Shimshal River valley of the Hunza basin. Khurdopin lake started to surge in the first week of May 2017 and it has been greatly expanded in terms of size and depth and it became vulnerable to breach as witnessed by the local people. Due to the short distance between the glacier and opposite hard mountain resulted in the rise of river bed and glacier as well as triggering the creation of Khurdopin lake. The velocity of the flow was reduced by the damming of water behind the barrier and this phenomenon also raised the river bed and blocked the river (**Figures 2** and **3**).

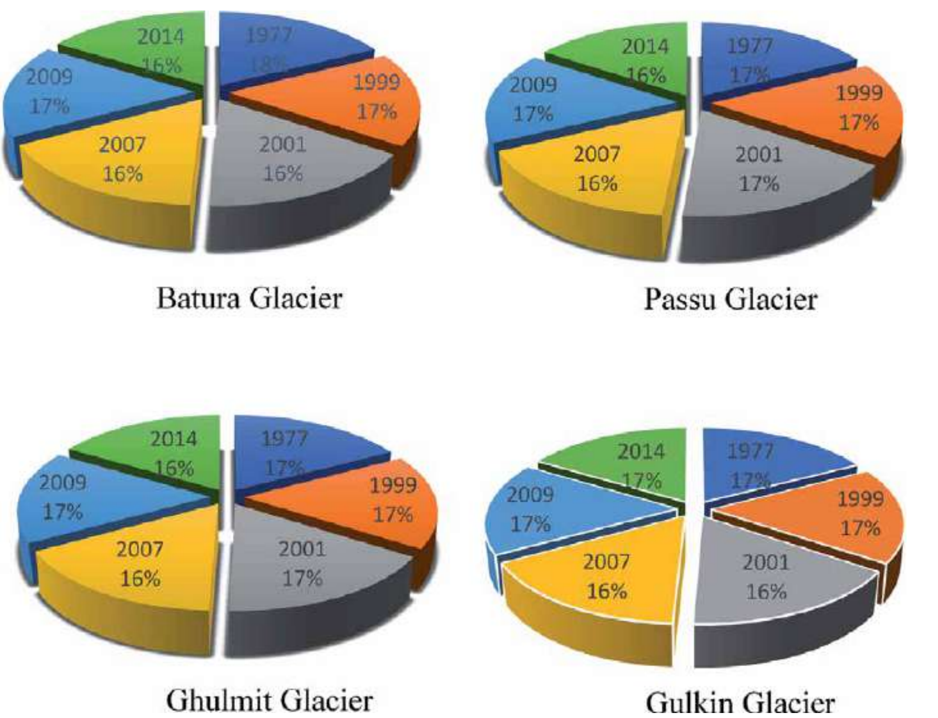

Figure 2.
Comparison of different glaciers area loss during the period of 1977–2014.

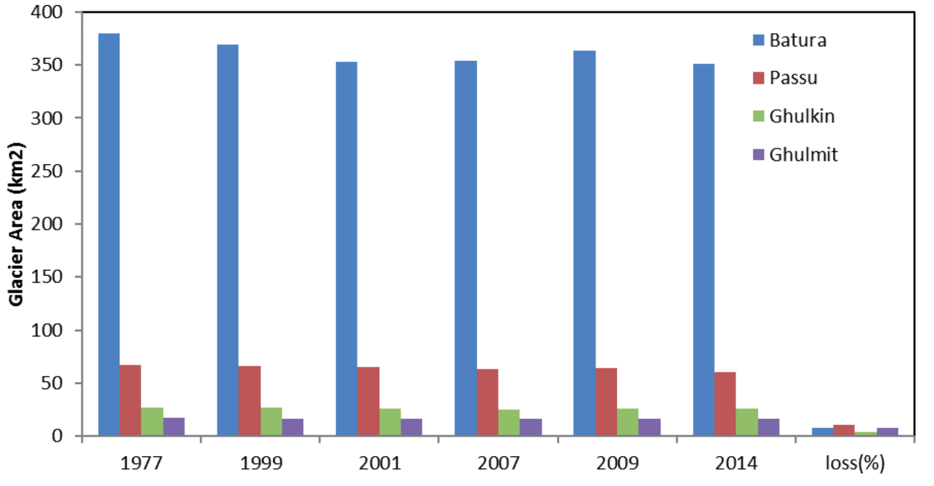

Figure 3.
Temporal variation in areas of different glaciers along CPEC.

The glacier areas of different glaciers were compared, which mostly thinned in terms of area or remain constant during the different periods. The area of Batura glacier was 380 km^2 in 1977 as compared to 351 km^2 in 2014, respectively. The loss of the area was 7.63% during this period. However, the glacier area loss was observed about 4.69% between 1999 and 2014. The glacier area was reduced to 369 km^2 till 1999 and lost 2.89% of the glacier area as compared to 1977. The loss in glacier area was increased by up to 7% in 2014 as compared to 1999. The increment of a 4% loss in glacier area was due to an increase in temperature. During 2001 and 2007, the loss of glacier area was consistent, but it was observed 4.2% in 2009 as compared to 1977. Passu glacier area loss observed 10% from 1977 to 2014. The loss of the area was less than 1% for 1999 as compared to 1977. The rate of loss of the glacier area increased in 2001 and reached up to 3% but this rate reached up to 7% in 2007. The lake formation also fluctuated during this period. The number of GLOF and historical events was also observed during this period. Ghulkin glacier also lost its area up to 4% due to global warming from 1977 to 2014. Earlier 2000, Ghulkin glacier lost the area less than 1.5%. After 2 years, the loss of the glacier area was 6%. From 2001 to 2007, the melting of glacier and loss of its area remained constant but the rate of glacier area loss was reduced up to 4% in 2009. Ghulmit glacier lost its area about less than 2% before 2000. The loss of the glacier area in 2001 was 4% but it increased up to 5% in 2007. This glacier area was reduced to 3% in 2009 as compared to 2007 (**Table 3**).

4.3 Drifting mechanism of glaciers

Due to differential movement of glaciers, crack or rift is produced in the glaciers having connected snout. A rift was formed along the left part of the Khurdopin glacier due to collapsing and crushing of glacier all together. The Yukshin Girdan glacier played a role of strong obstruction, produced massive frictional forces, and initiated the glacier ice to break down at the rift area into pieces of ice bergs that were seen floating on the newly formed lake. During this process, the Khurdopin glacier was forced by the Yukshin Girdan glacier to move toward the right side because of the unavailability of an obstacle to the opposite mountain. The elevation of the glacier at the rift area was about 3558 m a.s.l. The glacier was covered by a huge amount of debris during 2015, and after this surge, the debris began to falling

Sr.#	Glacier name	Glacier type	Area (km^2)
1	Batura	Debris cover	236
2	Passu	Debris free	51
3	Barpu	Surge type	90
4	Hispar	Surge type Debris cover	345
5	Yazghil	Debris cover	99
6	Khurdopin	Debris cover Surge type	115
7	Vijerab	Debris cover Surge type	113
Whole region			2868

Table 3.
List of selected glaciers and their types in Hunza basin [20].

and sliding into the crevasses and impacted the sub-glacial water movement and that may further result in the formulation of a new sub-glacial lake [25, 34].

The meltwater released from the Vijerab glacier was blocked by the Khurdopin glacier and it was muddy because of high sediment load coming from the glaciated area. A large amount of water was flowing through the newly developed crevasses due to the presence of barriers and ultimately outflowing through the cave type snout of Khurdopin glacier. The phenomenon of ice block falling in the stream of Vijerab glacier and on the supra-glacial lakes was also perceived. Because of surging effects, glacier deforms and results in the formation of huge crevasses. Three main types of crevasses developed in Khurdopin glacier are listed below: irregular crevasses, longitudinal crevasses, and transverse crevasses. Due to the demolishing action of glaciers, most of the crevasses were found to be irregular in shapes. Due to glacier advancement, large numbers of crevasses were developed all over the glacier. The width of the crevasses was variable at different locations and mostly, it ranged between 1 and 2.0 m [20, 35].

4.4 Geodetic mass balance of surging glaciers

The heterogeneous behavior and close-to balanced budgets are not a recent phenomenon in Hunza Valley (Karakoram). We have observed that the geodetic mass budgets computed from the 1973 KH-9 and 2009 ASTER DTMs are in covenant with the results of the individual periods 1973–1999 and 1999–2009 without indefinite radar penetration correction: since the 1970s, the glaciers in this region underwent slight and insignificant mass loss. Though, the differences may exist in individual glaciers for the two studied periods. Overall, we can confirm that the surge-type and non-surge-type glaciers are not significantly different with respect to mass change inferred from the 40 years observations of glaciers in the Karakoram (**Figure 4**).

One can easily assess the flood damages from recently developed lakes if it bursts based on watermarks of previous flood events. Besides, the bursting mechanism and the volume of flood events can give us an insight into the damages in the downstream areas. The water level in the lake can provide us information about the GLOF impacts on downstream infrastructure. The GLOF will have devastating impacts on the infrastructure including homes, lands, schools, etc. The settlement along the river site could be adversely affected as a result of GLOF (**Figure 5**).

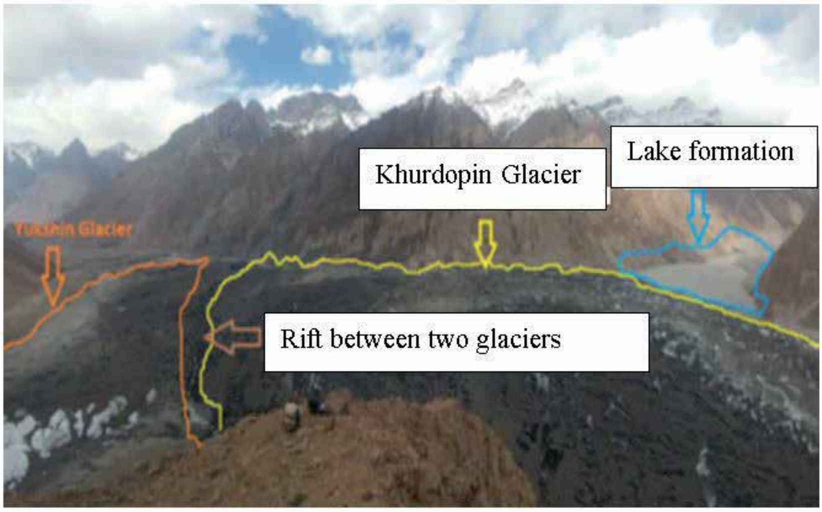

Figure 4.
Khurdopin Glacial Lake formation.

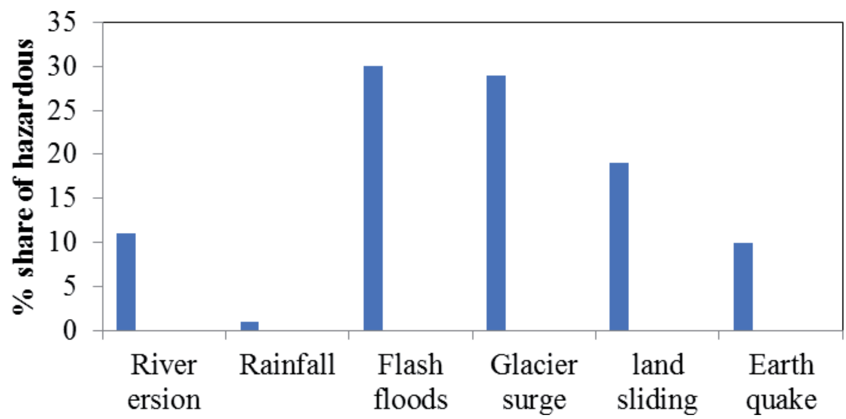

Figure 5.
Contribution of hazardous share in different glaciers along CPEC.

4.5 GLOF events associated with end-moraine dammed lakes

During 2001, the total numbers of lakes in Gilgit were 614. The total area of these lakes was 39.2 km^2. Out of 614 lakes, 380 were major and 8 were potential GLOF lakes. There were 110 glacial lakes in the Hunza basin, which have a total area of 3.2 km^2. Out of 47 glacial lakes, only one lake was potential GLOF, that is, Passu lake which has a potential threat to CPEC (**Figures 6** and 7). In the past, this lake had busted many times during the flooding period as given in **Table 2** and **Figures 6** and 7.

Amongst the end moraine dammed lakes of Hunza Basin, six were identified as potentially hazardous lakes for the CPEC route (**Figures 6** and 7). The major lakes were valley type and superglacial lakes. Passu lake was observed as a hazardous lake, which is near to Passu glacier. The surface area of this lake was 0.12 km^2, length 26 km, and thickness of about 173 m. The population of the Ghulkin, Hussaini, and Passu villages are 1133, 621, and 863 persons, respectively. During the July 2007 and April 2008, heavy flooding occurred, this damaged the CPEC route.

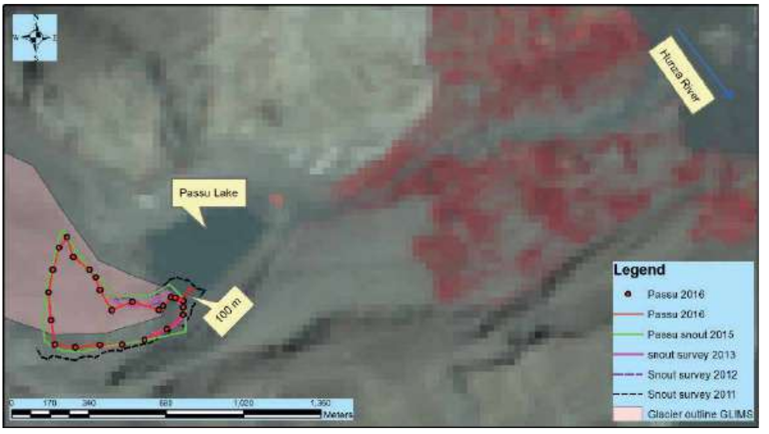

Figure 6.
Retreat of Passu glacier caused expansion in the glacial lake.

Figure 7.
View of the Passu glacier during 2011 and 2016 shows the expansion in lake area.

Basin	Number of lakes	Lake area	Major lakes	GLOF lakes
Gilgit	614	39.17	380	8
Hunza	110	3.22	47	1

Table 4.
Summary of glacial lakes in two major glaciered river basins along CPEC [20].

In July 2007, the lake was outburst with heavy flooding and another event was observed in April 2008. These events damaged the Karakoram Highway, hotels, and houses of the Passu village. This lake was breached several times in the past. Passu village is under high risk due to GLOF of this lake. There is a need to install the proper monitoring system to reduce the risks of glacier lakes outburst as well as local community protection in the downstream area (**Table 4**).

Although this lake is hazardous for the nearby communities of the Passu village and after the creation of a large land-slide dammed lake (Attabad lake) at Attabad during February 2010, the villages along Hunza River up to Gilgit and downstream became highly vulnerable of GLOF hazard. Early warning systems and proper monitoring can reduce the risk of damage to the CPEC route, infrastructures, and community. The different lakes of Gilgit have different rates of expansion such as 1.2, 0.4, and 0.3 ha/year during 2001 and 2013, respectively (**Figures 8–10**).

Figure 8.
Field observation of Passu glacier and lake.

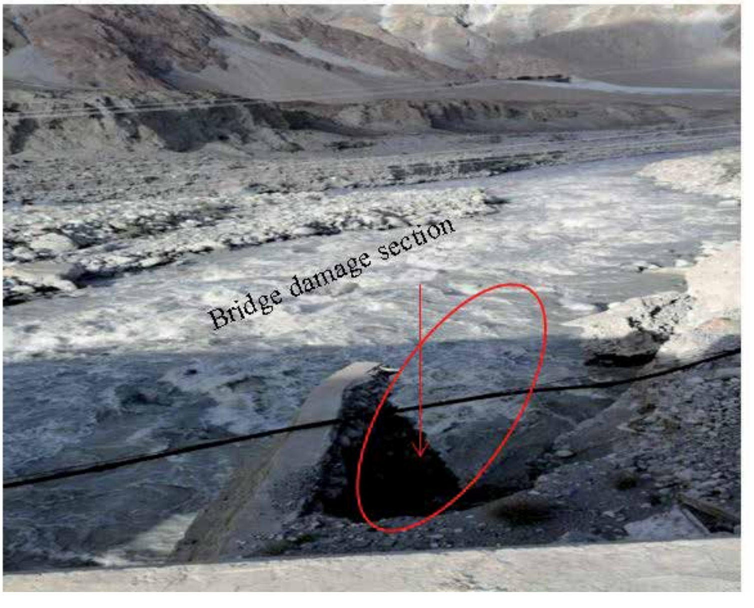

Figure 9.
Impact of high flow of Batura glacier on CPEC bridge.

5. Conclusions

The rugged topography and remoteness of the study area is a hurdle in the way to study the detailed processes and reasons behind the creation of glacial lakes along the CPEC. However, remote sensing techniques along with field surveys helped us to study the remote lakes along the CPEC route in the Hunza River basin. It was inferred from the analysis that the glaciers and glacial lake dynamics are interconnected to each other. The glacial lake dynamics is a complex phenomenon along CPEC. Gradually, lake dynamics has increased the risks of vulnerability along CPEC. Many potential lakes in the study area have the capability to damage the infrastructures as well as routes. Several GLOF events have been reported, especially, in the eastern part of the CPEC region during the last 50 years. Recently, Shisper Glacier damaged

Figure 10.
(a) Shisper glacier and its recent impact on CPEC route; (b) view of Passu glacier and CPEC route alignment.

the CPEC route and blocked it (**Figure 10a**). In the same way, the repeated surging of Khurdopin and Passu glaciers also resulted in the formation of high altitude glacial lakes in the Hunza River basin. We found that the type of GLOF event for the glaciers in the Hunza River basin is not the same. The aerial expansion of these glacial lakes increased due to global warming. Several glaciers are retreating in this region; this retreating will result in reduced river flows which in turn will affect the available run-off for irrigation and power generation. Moreover, the history of Khurdopin glacier's surge events revealed that the thermal phenomenon causes these surges. Moreover, it was perceived that the Passu Glacial Lake expansion is due to the retreat of the glacier (**Figure 10b**). However, the structure of the glacier surface suggests that its advancement is due to an increase in slope. A maximum increase in lake area was observed below 3500 m elevation, exhibiting a situation favorable for water resource management. The climate and hydrodynamics also influence the glaciers and glacial lakes. The CPEC initiative will bring a revolution in the lives of over 3 billion people in this region. Being the shortest route to the Middle East, Africa and Europe, it will benefit all partner countries and will boost their economies. However, there is a need to study climate change impacts on glaciers dynamics and lakes formation in the vicinity of CPEC to secure the route from future vulnerabilities and disasters.

Acknowledgements

This study is supported by the NSFC-ICIMOD joint project and other grants (Grant no. 41761144075 and 209071). We are thankful to the Water and Power Development Authority (WAPDA) of Pakistan for providing the required information data. We are thankful to the editor and associate editor, as well as reviewers for their valuable comments and suggestions to improve this chapter.

Conflict of interest

There is no conflict of interest.

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Chapter 7

Close-Range Sensing of Alpine Glaciers

Daniele Giordan, Niccolò Dematteis, Fabrizio Troilo, Valerio Segor and Danilo Godone

Abstract

Glacial processes can have a strong impact on human activities in terms of hazards and freshwater supply. Therefore, scientific observation is fundamental to understand their current state and possible evolution. To achieve this aim, various monitoring systems have been developed in the last decades to monitor different geophysical and geochemical properties. In this manuscript, we describe examples of close-range monitoring sensors to measure the glacier dynamics: (i) terrestrial interferometric radar, (ii) monoscopic time-lapse camera, (iii) total station, (iv) laser scanner, (v) ground-penetrating radar and (vi) structure form motion. We present the monitoring applications in the Planpincieux and Grandes Jorasses glaciers, which are located in the touristic area of the Italian side of the Mont Blanc massif. In recent years, the Planpincieux-Grandes Jorasses complex has become an open-air research laboratory of glacial monitoring techniques. Many close-range surveys have been conducted in this environment and a permanent network of monitoring systems that measures glacier surface deformation is presently active.

Keywords: Mont Blanc, monitoring, remote sensing, data integration, glacial hazards

1. Introduction

Mountain glaciers represent the main source of fresh water for human activities of the surrounding regions [1, 2]. Furthermore, glaciological processes (e.g. ice break-offs, glacier outbursts, snow/ice avalanches) can threaten population, urban areas and infrastructures [3]. In densely populated areas, such as the European Alps, the interaction between glaciers and anthropic activities is very frequent and it is of crucial importance to study the glaciers to understand their evolution and response to climate change, which is expected to reduce their area coverage and increase their instability [4].

Long-term monitoring of glaciological processes is often complicated and expensive, especially in remote areas and inaccessible terrains, which are common in mountain environment [5]. A practical approach is the adoption of remote sensing apparatuses that allow observing glacial processes with minimal risk for scientists and technicians. In recent years, the free availability of data acquired from satellite platforms has largely improved the possibility to observe wide areas from remote with relatively high spatiotemporal resolution. Nevertheless, satellite surveys suffer complex geometries and the revisit time might be not adequate to measure fast processes. Therefore, the use of close-range remote sensing systems is often the most effective solution for glacier monitoring [6].

Section 2 presents a substantial list of close-range remote sensing techniques that can be adopted to measure glacier surface deformations. Section 3 is devoted to the Planpincieux and Grandes Jorasses glaciers (Mont Blanc massif) case study (**Figure 1**). In recent years, such a glacial complex has become an open-air laboratory where innovative and experimental monitoring systems have been developed [6–12]. Several practical examples of close-range remote sensing surveys will be described therein.

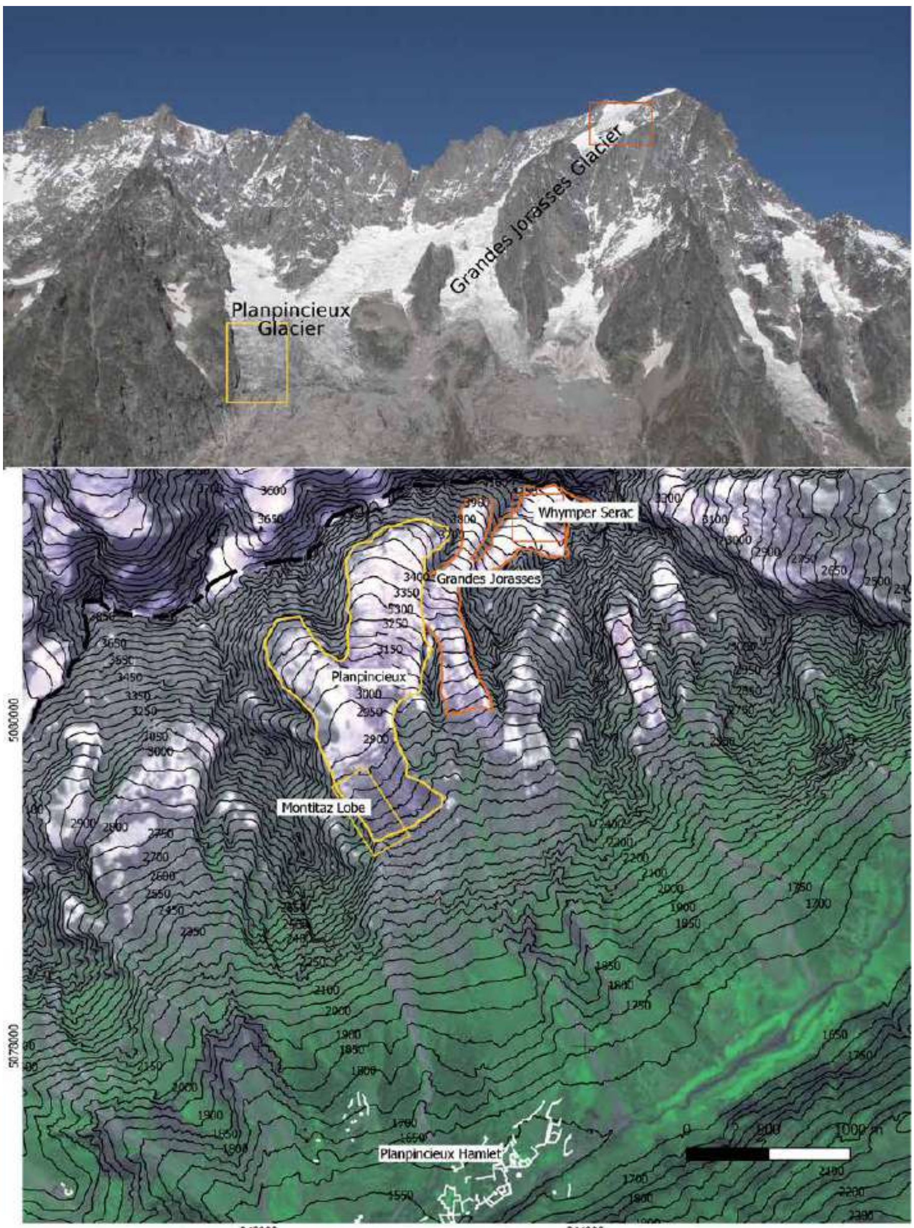

Figure 1.
*Overview of the Planpincieux and Grandes Jorasses glaciers (upper tile) and area of study (lower tile). Yellow and orange rectangles indicate respectively the Montitaz Lobe and the Whymper Serac framed by the time-lapse cameras (**Figure 2**).*

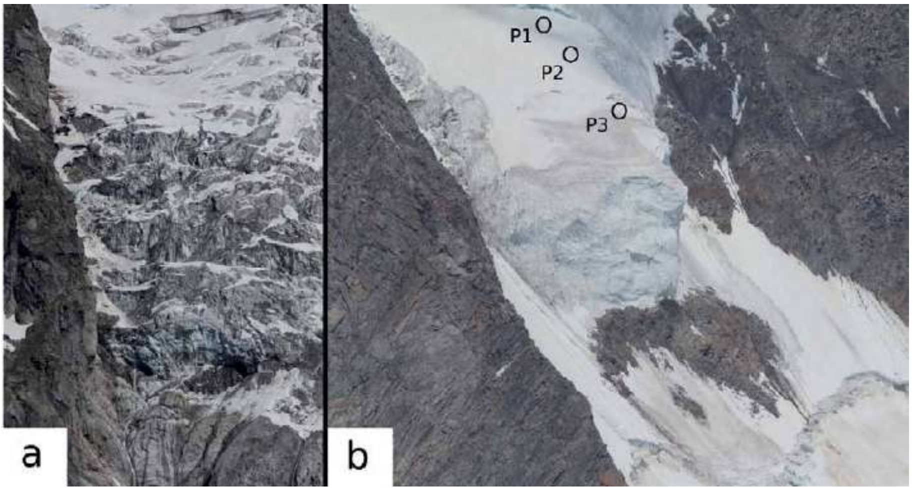

Figure 2.
(a) Image of the Montitaz Lobe of the Planpincieux Glacier monitored by a monoscopic time-lapse camera. The terminus width is approximately 100 m. (b) Image of the Whyper Serac acquired by monoscopic time-lapse camera. The serac face is approximately 40-m high. The black circles indicate the prism positions onto the serac surface in 2019.

2. Close-range remote sensing techniques

The study of the Planpincieux and Grandes Jorasses glacier surface deformations has been conducted following different approaches: (i) volumetric changes have been evaluated with point clouds and digital elevation models (DEMs). Such measurements have been obtained with laser scanners or structure from motion (SFM) processing. (ii) Surface kinematics maps of specific displacement components, which have been provided by monoscopic time-lapse camera and terrestrial interferometric radars. (iii) 3D displacements measured in specific points with a robotised total station (RTS). Furthermore, helicopter-borne ground-penetrating radar (GPR) campaigns have been conducted to investigate the glacier internal structure and thickness (**Table 1**).

2.1 Point clouds for surface generation

Three-dimensional point clouds are crucial tools in glacier monitoring; the main survey techniques to obtain them are LiDAR [13], terrestrial laser scanner (TLS) [14] and aerial and terrestrial photogrammetry, particularly structure from motion (SfM) approach [15]. LiDAR and TLS are based on a sensor, terrestrial or airborne, capable of emitting laser pulses at high frequency and measure their 'time of flight' in order to compute the position of each echo. The absolute position of each point is calculated from the emitter centre, geocoded by a GNSS coupled with an inertial measurement unit [16]. Besides its coordinates, each point can be characterised by the intensity of the echo in order to detect the nature of the target [17]. By the exploitation of laser beam divergence, it is also possible to discriminate and analyse multiple echoes or even the full waveform, thus obtaining multiple measurements of different object hit by the same pulse [18].

Concerning SfM, it is a technique originating from computer vision, which, by processing multiple images from different points of view of the same target object, generates a three-dimensional point cloud. The algorithm matches common

Glacier	Survey	Dates	References
Planpincieux	GPR	2/4/2013,	
		2019	
	DIC	August 2013-in	[8]
		course	
	TRI	9/8/2013-	[9, 42]
		10/8/2013	
		7/8/2014-	
		8/8/2014	
		1/9/2015-	
		14/10/2015	
		13/6/2016-	
		19/6/2019	
		26/9/2019-in	
		course	
	LiDAR	9/6/2014	
	TLS	2/10/2015	
	Helicopter-	2017	
	borne SFM	28/10/2018	
		20/9/2019	
		1/10/2019	
		5/11/2019	
	Drone SFM	24/7/2019	
Grandes	RTS	2010-in course	[11, 12]
Jorasses			
	DIC	2016-in course	
	GPR	4/6/2010	
		2/4/2013	
	Helicopter-	July 2010	
	borne SFM		
	Drone SFM	July 2019	

Table 1.
List of the surveys conducted in the Planpincieux and Grandes Jorasses glaciers since 2010.

features in the images and reconstructs the three-dimensional coordinates of the matching points and of the cameras. Resulting points are then collected in the cloud [19]. Images can be captured by various kinds of sensors including cameras, smartphones and drones [20].

2.2 Punctual topographic displacement measurements

Robotised total station (RTS) is a topographic apparatus that measures the sensor-to-target range and the azimuth and zenith angles, which allow determining the target position in a 3D coordinate system whose centre corresponds to the

RTS itself. Typical measurement sensibility of best-quality RTS is of 1.5 mm and 0.5 arcsec, depending on the distance. The RTS is composed of a laser rangefinder and an electronic theodolite that measures respectively distance and angles. The RTS targets retroreflector prisms installed both in and outside the moving area. The latter ones serve as control points for measurement calibration and data corrections.

Since it is required to install prisms within the investigated area, the RTS cannot be considered a remote sensing device in a strict sense. Nevertheless, such installation is needed just once; thereafter, the RTS provides measurements from remote, strongly reducing human and financial costs for accessing the surveyed area. This holds especially when the RTS works in automatic target recognition (ATR) mode, with which it carries out autonomously the measurements. In geosciences, the RTS is widely used for gravitational slope phenomena, such as landslides [21, 22], volcanos [23] and glaciers [11, 12, 24].

2.3 Glacier surface kinematics maps

Spatially distributed data are a relevant tool in glaciological studies because they allow to analyse the surface kinematic patterns and to identify possible different kinematic sectors. In the Planpincieux-Grandes Jorasses glacial complex, two main remote sensing systems have been applied to measure surface kinematics maps: digital image correlation (DIC) and terrestrial radar interferometry (TRI).

2.3.1 Digital image correlation

With the advent of digital cameras, time-lapse imagery has become popular since the beginning of the 2000s in glaciology, where it has been applied to survey polar ice flow [25–28] and mountain glaciers [6, 8, 29–33].

DIC is an image analysis technique that is applied to a pair of images to obtain spatially distributed maps of the two displacement components orthogonal to the line-of-sight (LOS). In classical DIC processing, a reference template out of the master image is searched for in an investigated larger area of the slave image. The cross-correlation (CC) is calculated for every possible template of the investigated area and the position of the maximum correlation coefficient corresponds to the displacement of the master template. Alternatively, the CC can be calculated in the Fourier domain according to the convolution theorem. Fourier CC is computationally efficient but it is more prone to outliers.

The main DIC advantages concern the low-cost hardware and its high portability even in harsh environments. Nevertheless, it suffers adverse meteorology and it strongly depends on the visibility conditions.

2.3.2 Terrestrial radar interferometry

In the last two decades, TRI revealed to be a valuable tool to monitor glaciers [9, 34–42]. TRI concerns the analysis of the phase difference between two radar acquisitions, which is directly related to the target displacement component parallel to the LOS. Typical radar apparatuses can provide spatially distributed displacement data in an area of several square kilometres with an operative range of a few kilometres. Radars are active sensors, as such, TRI can be applied during the night and severe meteorological conditions. Moreover, TRI measurements have sub-millimetre sensibility in an optimal context. However, the processing is not trivial and it requires high computational costs. Particularly complicated is the phase wrapping solution, which depends on the phase 2 periodicity and which is related to the sensor-to-target range. Moreover, TRI is quite sensitive to possible morphological change of the scattering surface and that causes signal decorrelation and extreme atmospheric conditions can heavily affect the measurements [43, 44]. In glaciological contexts, long distances, morphological surface changes and severe meteorology are common and TRI processing must be handled carefully.

2.4 Glacier internal structure

GPR has been widely used as a geophysical method for the study of internal glacier properties. A variation in electrical permittivity creates dielectric interfaces and subsequent reflections that can be analysed. GPR can be used for the definition of firn-ice transition, the detection of subglacial cavities and the ice thickness [45]. GPR systems include a transmitter and a receiver antenna. Typical operating frequencies vary between 10 and 15 MHz, for the investigation of glaciers having depths of hundreds of meters, to 400–600 MHz, for shallow investigations. Different factors can limit the effectiveness of the technique, such as debris cover of the ice surface or highly crevassed areas that can create scattering or absorption phenomena that reduce the possibility of investigation of the glacier sub-surface. Processing of radar data normally implies many steps, which include (i) low-frequency filtering, caused mainly by surface reflection; (ii) selection of a time gain to correct for the amplitude divergence; (iii) temporal and spatial filtering for improving the signal-to-noise ratio; (iV) deconvolution and (v) migration [46].

GPR apparatuses are usually lightweight and compact and they can be easily transported by walking or snowmobile, which allows at acquiring a large number of 2D radar profiles. However, helicopter-borne surveys provide the most versatile platform and they have been used for detecting glacier thickness [47, 48], intraglacial features [49] and snow accumulation [50].

2.5 Data integration

Spatially distributed deformation data provide wide information on the investigated process. Nevertheless, common remote sensing apparatuses only provide specific displacement components or punctual measurements and the integration of different sensors is necessary to obtain spatially distributed 3D data.

Dematteis et al. [6] proposed an innovative solution to obtain 3D displacement using DIC and TRI data integration. DIC and TRI provide different and complementary displacement components that can be coupled to obtain a three-dimensional representation of the surface kinematics. The necessary conditions to couple the different data are that their maps must have the same spatial resolution in the same coordinate system (CS). Therefore, a geometric transformation is required to represent both data in the same CS, which is usually associated with a georeferenced DEM.

A different approach of data integration entails the merging of DIC and RTS data. RTS provides 3D displacement in specific points, while DIC can measure spatially distributed data. Therefore, their integration allows obtaining the displacement direction and versus using RTS data, while the DIC results give the spatial distribution.

3. Case study: Planpincieux-Grandes Jorasses glaciers

The Planpincieux and Grandes Jorasses glaciers form a unique polythermal glacial complex located on the Italian side of the Grandes Jorasses peak (Mont

Blanc massif), in the Ferret valley (**Figure 1**). The glaciers have approximately a South-East aspect and the elevation ranges from 2600 m asl to 4200 m asl. The accumulation area of the Grandes Jorasses Glacier is formed of two 45° steep cirques, which merge in an icefall at 3500 m asl. In the left cirque is located the Whymper Serac, whose front is at an elevation of 3800 m asl (**Figure 2b**). According to Pralong and Funk [51], this portion is classified as an unbalanced hanging glacier. As such, the serac progressively increases its volume and when its shape reaches unstable geometry, the serac collapses. This cycle follows an irregular periodicity and the time between the break-offs ranges from a few years to more than a decade. Usually, the unstable ice chunk has a volume of the order of 105 m^3, which can collapse at once or in several pieces. The instability dynamics is driven only by the geometry and it is not linked to temperature or water percolation. Therefore, the fracture can also occur during the cold season, when the collapse might easily trigger a large snow avalanche that would seriously threaten the underlying buildings and the road at the valley bottom. The last events happened in August 1993, June 1998 [11] and September 2014 [12]. The first one caused the fatality of eight mountaineers, but the ice avalanche did not cause further damages for the absence of snow.

The Planpincieux Glacier topography presents three distinguished zones: the accumulation area, 3000–3500 m asl, is formed of two steep cirques that merge in a wide plateau at 2900–3000 m asl, and two lobes constitute the ablation area. The right lower lobe (**Figure 2a**) is 32° steep on average and it is quite crevassed. Its terminus ends in correspondence of a bedrock cliff that causes frequent calving. In the past, several collapses occurred and, in a few cases, they endangered the bridge of the Montitaz stream that originates from the glacier snout. Further information on the Planpincieux Glacier can be found in Giordan et al. [7].

3.1 Monitoring campaigns

In the last decades, the Planpincieux-Grandes Jorasses Glacier complex has become an open-air laboratory where innovative remote sensing techniques have been developed to monitor the glacier activity [6–12].

The Planpincieux Glacier is observed by two monoscopic time-lapse cameras placed in the opposite side of the Ferret valley, at a distance of 3800 m from the glacier. The monitoring station is equipped with two solar panels and an electric cell for power supply. It is remotely controlled by a Raspberry Pi 3 connected to the server of the Geohazard Monitoring Group (GMG) of the Research Institute for Geo-Hydrological Protection (IRPI), in Torino, Italy. A robotised webcam has been installed in 2018 to survey the station functioning. The system is active since August 2013 and it acquires images at hourly frequency. In the period August 2013–December 2019, it collected more than 35,000 images and it is probably the longest continuous series of hourly images in the European Alps. The images are processed with the DIC technique to estimate the surface glacier kinematics.

The Grandes Jorasses Glacier is being monitored since 2010 by an RTS installed in the Planpincieux hamlet at a distance of 4800 m. The RTS measures every 2 h the position of the prisms installed onto and in the vicinity of the Whymper Serac (**Figure 2b**). Due to the extreme meteorological conditions and the exceptional sensor-to-target range, the prisms are not always visible and gaps in the measurement series are frequent, especially during the cold season. Snowfalls and strong wind occasionally cause the loss of some prisms and the intervention of Alpine guides it is necessary for the installation of new targets. Moreover, the Whymper Serac is continuously monitored by a 4800-m-far monoscopic camera. This survey is active since 2010 and the serac surface displacement is estimated with feature tracking of the hourly photographs.

Besides these continuous monitoring systems, in the past, several measurement campaigns have been conducted to increase the glacier understanding and to develop new monitoring techniques of glaciological close-range remote sensing. In **Table 1**, the complete list of the surveys conducted since 2010 is presented and the related references are reported when available.

3.1.1 Point cloud analysis

DEMs obtained during LiDAR and TLS surveys and from photographic SfM acquired by drones and helicopter-borne cameras allow monitoring the morphology evolution of the glacier surface. In addition, the DEM of difference (DoD) calculation permits to estimate the surface elevation changes and the possible ice mass loss. From the DoD obtained with the DEMs acquired in October 2019 and June 2014 (helicopter-borne SfM and LiDAR respectively), one can observe the glacier thinning of more than 10 m on average (**Figure 3**). In the considered period, the terminus retreated by several tenths of metres and the bedrock remained exposed. In this part, the DoD shows a thickness loss of 30–40 m approximately, which corresponds to the glacier thickness in 2014.

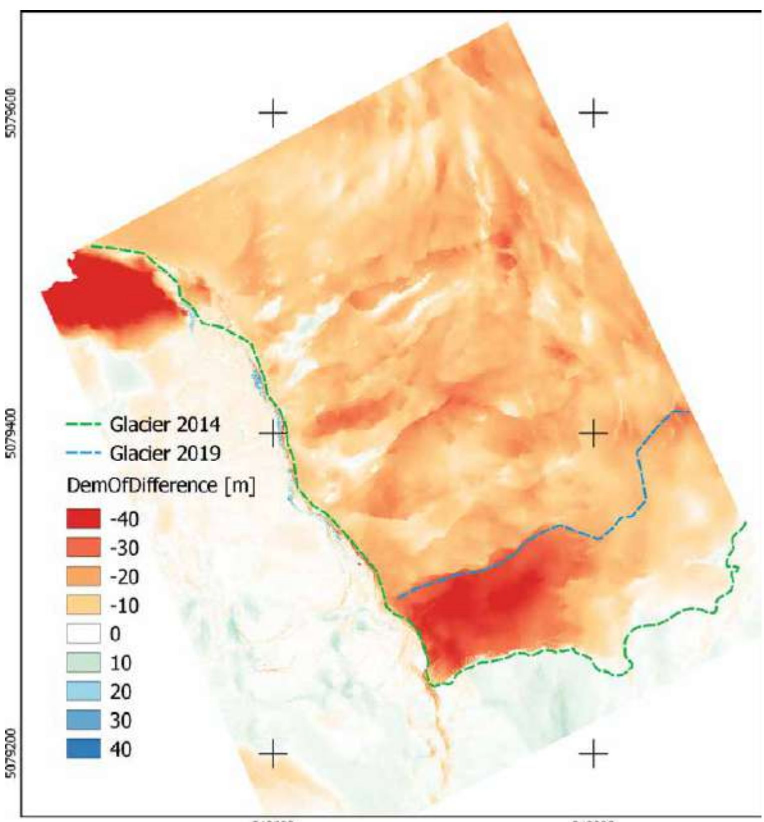

Figure 3.
DEM of difference (DoD) of the Montitaz Lobe. The DoD is calculated as the difference between the DEMs acquired on 1/10/2019 and 9/6/2014. The glacier outlines in both years are represented as dashed lines.

3.1.2 RTS applications

RTS measurements are continuously active since 2010 to monitor the surface velocity of the Whymper Serac. The survey is conducted with a Leica TM30 that operates in ATR mode. The prism network is composed of several stakes installed into the unstable portions, while a few prisms placed in the surrounding bedrock serve as reference points. Complete acquisition of the entire network lasts approximately 45 min and it is conducted every 2h. The sensor-to-target distance is of 4800 m on average, which is beyond the instrument operating limits declared by the manufacture in ATR mode (https://w3.leica-geosystems.com/downloads123/zz/tps/tm30/brochures-datasheet/tm30_technical_data_en.pdf). In addition, extreme atmospheric conditions linked to the high-mountain elevation occur frequently. This situation makes the Whymper Serac a critical scenario for RTS measurements and a robust processing method has been developed ad hoc [11]. However, the RTS data allowed forecasting 10 days in advance the serac break-off of 22/10/2014 [12]. The RTS data acquired before such an event are shown in **Figure 4**.

3.1.3 Time-lapse camera applications

The surface kinematics of the Planpincieux Glacier right lobe has been deeply investigated with image analysis of 6-year-long time-lapse monitoring. The data analysis allowed characterising the terminus dynamics and classifying the instability processes that cause break-offs: (i) disaggregation, (ii) slab fracture and (iii) water tunnelling [7]. Disaggregation is the progressive toppling of small ice pieces caused by the movement of the terminus beyond the frontal bedrock cliff. It is the most frequent process and it involves break-offs of limited size, usually lower than 1000 m^3. Slab fracture instability is caused by the aperture of a crevasse orthogonal to the motion direction, located in correspondence to the maximum tensile stress line. When the fracture reaches the bedrock, it triggers a large break-off of an ice lamella that can assume a volume of 104–105 m^3. Water tunnelling refers to the formation of R-channels [52] where a large amount of

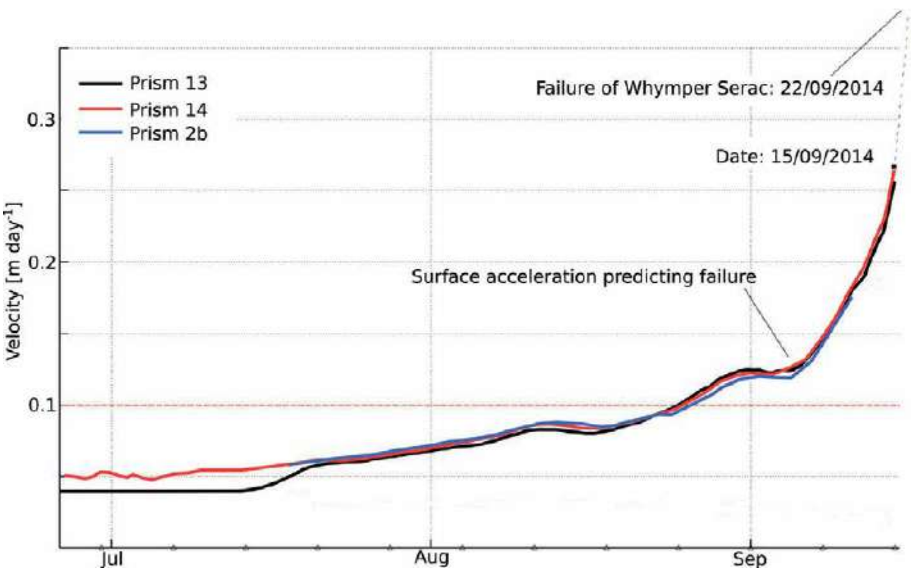

Figure 4.
RTS measurements of prisms 13, 14, and 2b before the failure of 22/09/2014. Using these data, the break-off was predicted 10 days in advance.

water can accumulate. The water produces a strong pressure on the frontal cliff that can provoke failure of the terminus. Moreover, the empty tunnels increase the instability and they can collapse themselves.

Besides the visual photographic interpretation, DIC in the Fourier domain was applied to the hourly images, obtaining surface displacement maps at daily resolution. During the monitoring period, the surface displacement pattern was composed of four distinct kinematic domains, which were characterised by different velocity regimes. The presence of kinematics domains indicates the action of high strain rates localised at the domain limits, where large fractures appear (**Figure 5**). The behaviour of the frontal sector is noteworthy, because it reveals the occurrence of a few speed-up periods per year, which culminate with large break-offs (**Figure 6**). These kinematic fluctuations were characterised by well-defined thresholds of initial velocity ($v_0 \geq 30$ cm day^{-1}) and acceleration ($a \geq 3$ cm day^{-2}). Moreover, a monotonic relationship (rank correlation coefficient > 0.7, p-value < 0.02) between the velocity peak and the collapsed volume has been observed.

DIC in the spatial domain was applied to the images of the Whymper Serac to measure the displacement in July 2019 (**Figure 7a**, **b**). The available images presented rototranslation that had to be compensated with robust coregistration. Moreover, the smooth texture and low chromatic contrast of the scene lowered the signal-to-noise ratio (i.e. the correlation, see **Figure 7**) and hence many artefacts were present in the displacement maps. Therefore, a robust outlier correction method was applied [53]. The results showed a slight acceleration during July, which was confirmed by RTS measurements.

3.1.4 TRI applications

The Planpincieux is probably the unique glacier where TRI surveys were conducted using four different terrestrial interferometric radar models, namely: GPRI™ (Gamma Remote Sensing, https://www.gamma-rs.ch/rud/microwave-hardware/gpri.html), IBIS-L™ (IDS Georadar, https://idsgeoradar.com/products/interferometric-radar/ibis-fl), FastGBSAR-S™ (MetaSensing, https://www.geomatics.metasensing.com/fastgbsar-s) and GBInSAR LiSALab™ (LiSALab, http://www.lisalab.com/home/default.asp?sez=6).

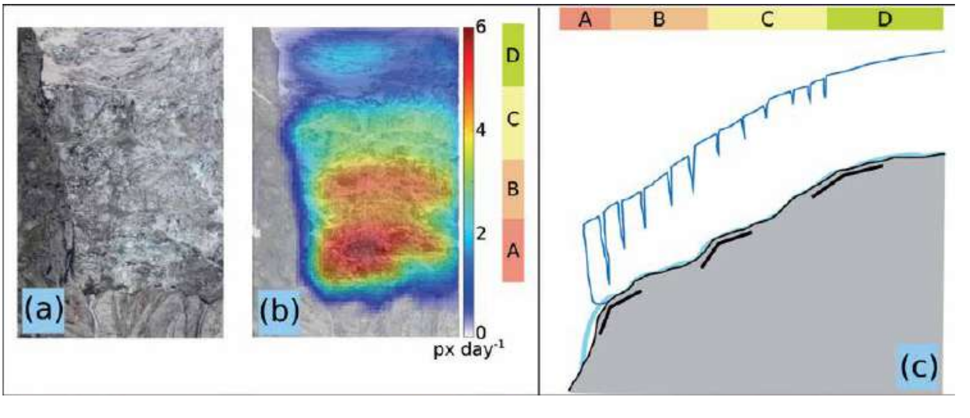

Figure 5.
(a) Image of the Montitaz Lobe acquired by the monoscopic time-lapse camera. The terminus width is approximately 100 m. (b) Surface deformation map. Different velocity regimes clearly identify the four kinematics domains. (c) Longitudinal conceptual scheme of the glacier lobe (not in scale). The black lines indicate bedrock discontinuities that correspond to the kinematic domain limits. Modified from Giordan et al. [7].

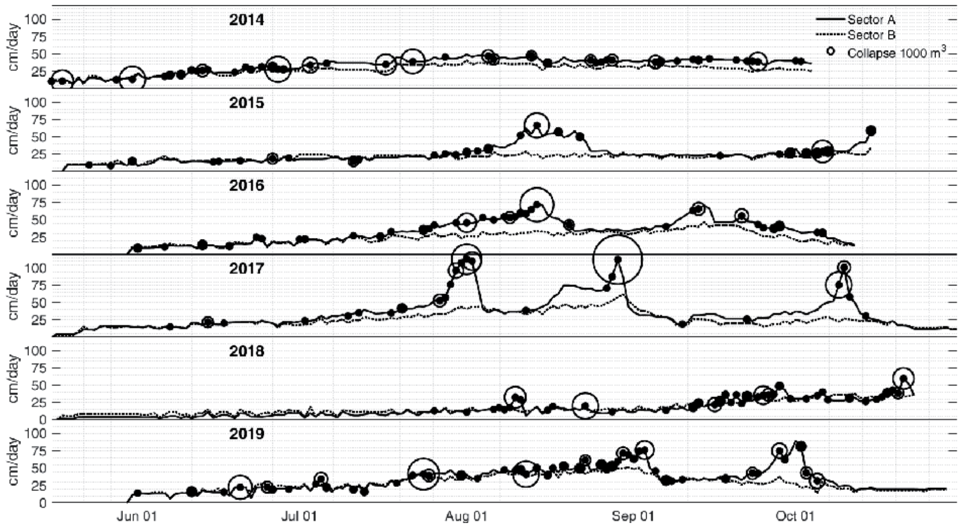

Figure 6.
*Time series of the daily velocity of sectors A and B (see **Figure 5**) in the years 2014–2019 (from top to bottom). The break-off occurrence is depicted in black dots, while the white circle size is proportional to the volume.*

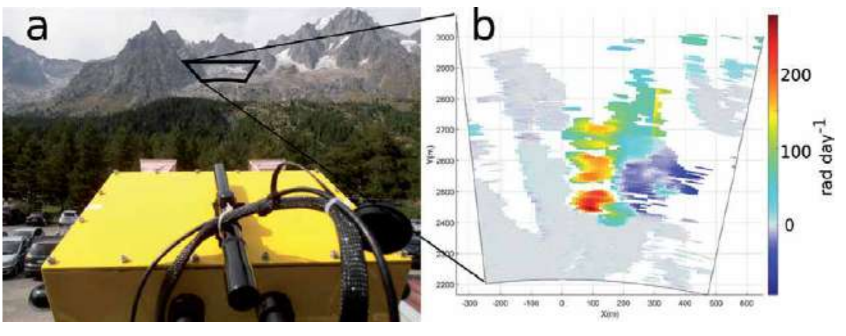

Figure 7.
(a) IBIS-L GBSAR surveyed the Planpincieux Glacier area, delimited in black. (b) The cumulative sum of the interferograms acquired in the period September 4, 2015 to October 14, 2015.

The surface kinematics of the glaciers was surveyed in five TRI campaigns, in 2013, 2014, 2015, 2016 and 2019 (**Table 1**). The first two were conducted using the GPRI™ real-aperture radar (RAR) in Ku band that surveyed the glacier from the valley bottom and the valley ridge opposite to the glaciers. Both campaigns lasted for 2 days and they were able to detect the displacements of the lower portions of the Planpincieux and Grandes Jorasses glaciers, which were approximately 25 cm day^{-1} and 50 cm day^{-1} respectively. Instead, the following surveys were conducted using Ku-band ground-based synthetic aperture radars (GB-SAR). The campaign of autumn 2015 (IBIS-L™) lasted much longer and hence it was possible to recognise the different kinematic domains of the Montitaz Lobe (**Figure 8**). During the campaign, the meteorological conditions were severe and the radar acquisitions were affected by strong APS. To solve the issue, a polynomial APS model that was a function of the topography was developed [9, 42]. In 2016, FastGBSAR-S™ measurements with an acquisition frequency of 10 s were carried out; thereby, the atmospheric disturbance was minimised. Fully polarimetric measurements were experimented, but the very long distance did not allow exploiting the potentiality of such a technology. The last campaign (GBInSAR LiSALab™) began at the end of September 2019 for civil protection and it is still active during the writing of the present chapter.

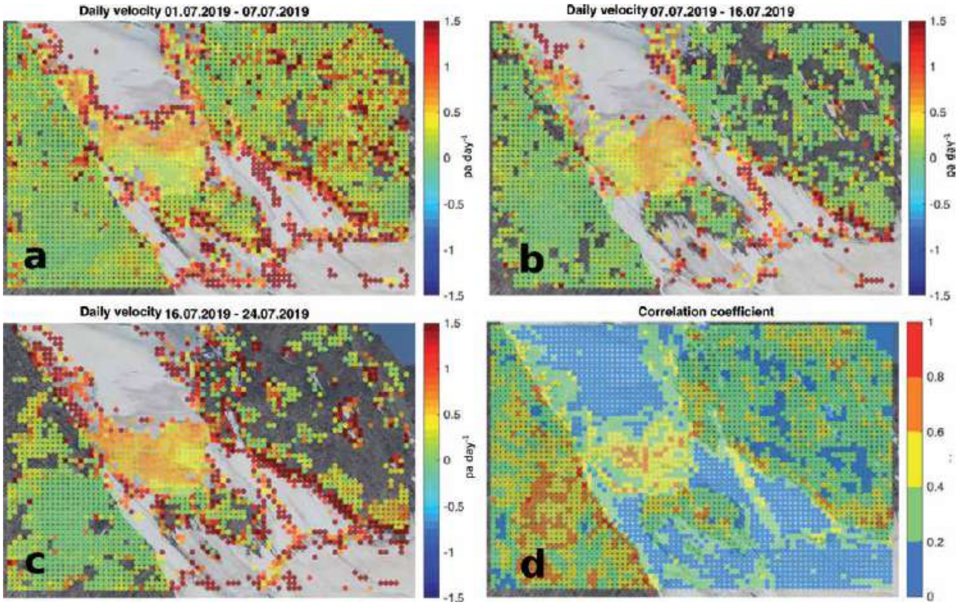

Figure 8.
(a-c) Surface displacement maps of the Whymper Serac of the periods July 1, 2019 to July 7, 2019, July 7, 2019 to July 16, 2019 and July 16, 2019–July 24, 2019. (d) Map of the mean correlation coefficient, which displays low values because of the texture smoothness of the snow surfaces. The serac face is approximately 40 m high.

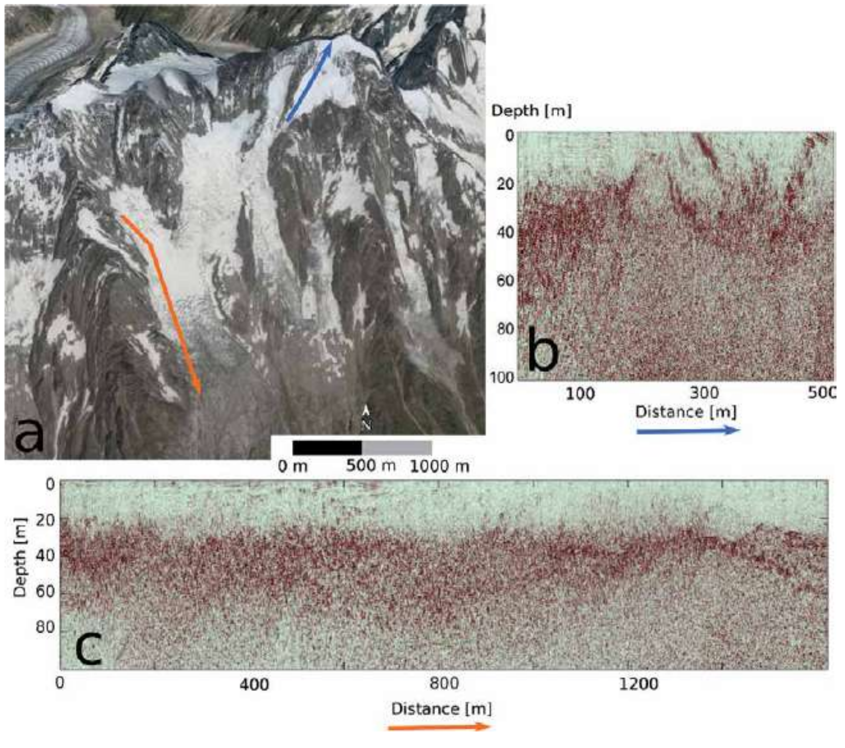

Figure 9.
(a) GPR traces of the Planpincieux (orange line) and Grandes Jorasses (blue line) glaciers. (b-c) GPR profiles of the Whymper Serac and Planpincieux Glacier respectively. The white-red boundary indicates the ice thickness.

3.1.5 GPR applications

A helicopter-borne 65-MHz GPR survey was conducted in the Planpincieux-Grandes Jorasses glacial complex in April 2014, when 16 GPR traces homogeneously distributed on the glaciers' surface were acquired (**Figure 9**). The noise of the radar data was quite high, because the numerous crevasses caused bounds of the electromagnetic waves and produced echoes and artefacts. Nevertheless, it was possible to estimate the glacier thickness, which was in the range 20–40 m in the Planpincieux Glacier and lower than 20 m in the Whymper Serac.

3.1.6 Data integration

In September 2015, time-lapse photography and terrestrial radar campaigns were conducted simultaneously to measure the Planpincieux Glacier surface kinematics. The actual three-dimensional surface kinematics was obtained by coupling DIC and TRI results. **Figure 10** reports the mean daily velocity map, where the colour represents the velocity module and the arrows indicate direction and versus. The 3D displacement can be obtained only in the areas visible by both the sensors. In the right lobe, the displacement vectors are not uniformly parallel to the surface, because the seracs move downstream as a single body and the ice is subjected to internal deformation. This result is not trivial, as the most common approach to estimate 3D displacement is to project the single movement components along the local slope obtained from the DEM, but this assumption might be misleading in specific cases.

The permanent monitoring system of the Whymper Serac is composed of RTS and time-lapse imagery. In July 2019, the data of the two sensors were integrated and represented in an informative bulletin [54, 55], shown in **Figure 11**. Such integration allows evaluating the versus and direction of the principal movement (with the RTS data) and the distribution of the strain rates (with the DIC results).

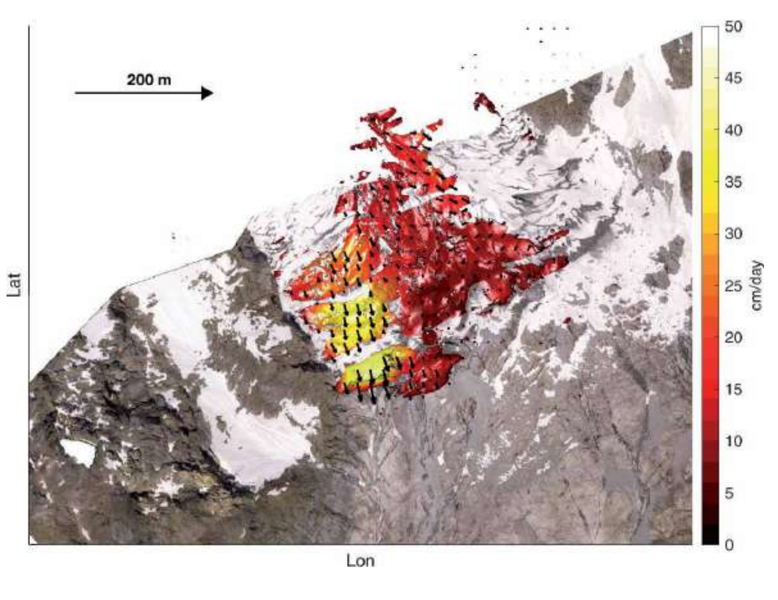

Figure 10.
Velocity field of the surface kinematics of the lower Planpincieux Glacier obtained with the integration of DIC and TRI measurements. Colours and arrows represent velocity module and direction respectively. Modified from Dematteis et al. [6].

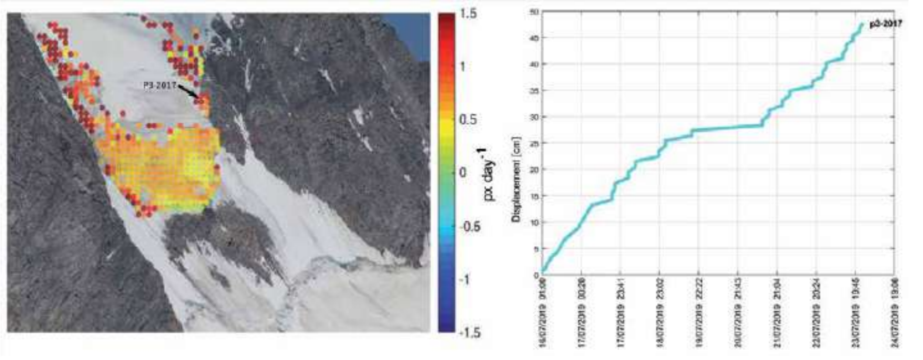

Figure 11.
Data integration of DIC and RTS measurements. The image depicts the spatially distributed daily deformation of the Whymper Serac front (coloured dots) and the surface displacement direction measured by the TRS in correspondence with the prism P3-2017. The right plot reports the displacement trend provided by the RTS.

4. Summary

In-depth knowledge of glacier behaviour is fundamental for glaciological risk evaluation and management and it permits to develop mitigation and adaptation strategies against the cryosphere change provoked by global warming. To achieve this aim, data collection about the current glacier state is of primary importance, but the harsh mountain environment makes the survey activities difficult. Measurements from aerospace platforms are affected by complex geometries and might not provide sufficient spatiotemporal resolution, especially when high acquisition rates (i.e. minutes to hours) are necessary. Therefore, ground-based systems are often the most suitable solution. Nevertheless, impervious areas where glaciers are usually located entail the use of high financial and human efforts, as well as potential risks to access the investigated area. Therefore, remote sensing systems represent the best cost-benefit ratio and they are commonly adopted for glacier monitoring. Considering the possible adverse conditions (e.g. extreme meteorology, steep slopes, long sensor-to-target distance, natural hazards) that can occur during the survey activities, ad hoc technologies and methods must be developed. The glacial complex formed of the Planpincieux and Grandes Jorasses glaciers represents an outstanding site where different close-range remote sensing approaches have been experimented, in a heterogeneous Alpine glacier environment. Here, the combined use of multiple sensors proved to be a valuable tool to collect complementary information that allowed improving the understanding of the current state and recent evolution of the glacial area.

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Chapter 8

Glacial Biodiversity: Lessons from Ground-dwelling and Aquatic Insects

Mauro Gobbi and Valeria Lencioni

Abstract

At first glance, the ground surrounding the glacier front and the streams originated by melting glaciers seem to be too extreme to host life forms. They are instead ecosystems, colonized by bacteria, fungi, algae, mosses, plants and animals (called the "glacial biodiversity"). The best adapted animals to colonize glacier surface, the recently deglaciated terrains and glacial streams are insects, specifically the ground beetles (carabids) and the non-biting midges (chironomids). This chapter aims to overview the species colonizing these habitats, their adaptation strategies to face natural cold and anthropogenic heat and the extinction threats of glacial retreat and pollution by emerging contaminants. Notes on their role in the glacial-ecosystem functioning and related ecosystem services are also given.

Keywords: carabid beetles, chironomids, cold-adapted species, debris-covered glaciers, extinction risk, glacier forelands, rock glaciers

1. Introduction

Insects are the most diverse and abundant group of animals on Earth and are critical drivers of ecosystem function in terrestrial and aquatic systems.

Biodiversity of insects is threatened worldwide [1]; 40% of the world's insect species could go extinct within decades [2] with consequent loss of ecosystem functions and services.

Despite the attention from the media, and scientific community, it remains unclear whether such declines are widespread among habitats and geographic regions. Since most of the insects are providing services (e.g., pollination and decomposition) and disservices (e.g., damaging crops and spreading diseases), the efforts in insect conservation biology and population management have been mainly conveyed to highly impacted areas like, for instance, the lowlands.

On the other hand, around the world, mountain regions are changing at an unprecedented rate. Most of the evidences are based on the abiotic component (e.g., temperature increase and precipitation variations), but there are increasing evidences about changes in biological communities.

At high altitude in tropical and temperate mountains and at high latitude, habitat loss, pollution and climate change affect negatively cold-adapted insect species distribution and survival [3, 4]. It is unlikely that insect declines will be homogenous everywhere, but some general patterns can be identified. For example, at high altitude, the high frequency of extreme climatic events and the loss of ice-related landforms (e.g., glaciers and rock glaciers) are detrimental to cold-adapted insects, highly specialized to survive constantly at low temperature, high humidity, deep snow and ice cover. Most of the glaciers are strongly reducing their surface, some are disappearing, others are shifting in debris-covered glaciers and permafrost is melting [5]. The effects of climate change on high-altitude terrestrial and aquatic insect community composition and ecosystem functioning are partially unknown and still underconsidered [6].

Scattered studies on high-altitude and high-latitude insect communities are available for most of the glacialized areas of the world, but a synthesis paper merging the most recent advances on cold-adapted insect species living on and at the edge of ice-related landforms is still not available. To fill this gap, the purpose of this chapter is to (i) describe what insects live in glacialized areas, (ii) examine what are the flagship insects in terms of richness and adaptation to cold, (iii) identify threats and opportunities in the current warm-period and (iv) illustrate the role of insect communities in the glacial-ecosystem functioning and services.

2. Glacial biodiversity: glacial and periglacial landforms as habitat for cryophilous species

At first glance, the ground surrounding the glacier front, its surface and the streams originated by the melting glaciers seems to be too extreme to host any life forms. Conversely, there are many organisms that permanently colonize the cryosphere, from bacteria to vertebrates, the so-called glacial biodiversity [7].

From the quantitative point of view, the glacial biodiversity is mainly formed by little (less of 5 cm) or microscopic organisms linked to aquatic, semiaquatic, wet or terrestrial (mainly bare and rocky grounds) habitats.

The surface of glaciers is colonized by bacteria and algae [8, 9] and mosses, hosting in turn water bears (Tardigrade), roundworms (Nematoda) and potworms (Enchytraeidae) [10]. They can live also directly on the surface of the ice, in cryoconite holes and rivulets on ice. In addition, on the glaciers, it is possible to observe wandering several spiders (Araneae) during the day as well as some ground beetles (Coleoptera: Carabidae) during the night searching for preys. Many other invertebrates, mostly connected with aquatic/wet environments, such as springtails (Collembola), stoneflies (Plecoptera) and non-biting midges (Diptera: Chironomidae), can live directly on the surface of the ice [11]. Moreover, supraglacial cryoconite holes can be considered biodiversity hotspots for invertebrates such as Copepoda, worms (Annelida), water bears, roundworms and wheel animals (Rotifera) [11, 12].

Most of the invertebrates living on the glaciers can be found also along recently deglaciated terrains and in the uppermost reach of glacial streams. Thus, the glacial biodiversity living at the edge with the glacier front arrives from two different sinks: falling down from the glacier surface during the melting phases and shifting up along the glacier forelands, transported airborne or by walking. Typically, springtails and moss mites (Oribatida) are the first colonizers of recently deglaciated areas because they are easily transported by the wind, thanks to their lightweight. Some sheet weaver spiders (Linyphiidae) are as well colonizers transported by wind [13]. Thus, recently deglaciated terrains act as a source of glacial biodiversity characterized by species living on the ground but still linked to the presence of cold microclimate ensured by the presence of the glacier few meters far from them.

Aquatic fauna in rivulets on ice (= eukryal) and uppermost reaches of glacier-fed streams (=metakryal) is represented mainly by cold hardy non-biting midges that have resistant forms to survive freezing and desiccation. Other guests of such habitats are worms (e.g., Naididae and Enchytraeidae) and free-living and parasite roundworms.

Similar to recently deglaciated terrains, also rock glaciers—which are the best expression of the periglacial environment in alpine areas—can sustain glacial biodiversity, also in the places where there are no glaciers or they disappeared. Currently, the state of knowledge about the animals living on this kind of landform is still very limited; just few sites in Sierra Nevada and on the Alps were investigated [14–16]. Both studies highlighted the presence of microbes, arthropods and small rodent fauna linked to the cold and wet habitat ensured by the presence of interstitial ice. Given the known thermal and hydrologic capacity of rock glaciers to resist warming, this distinct landform has been suggested as potential climatic refugia for glacial biodiversity in the current warm stage period.

It is therefore evident that glacial biodiversity is characterized by species living in ice-related landforms, thus landforms ensuring, at the ground as well as on the water, average annual temperatures around 0°C [17, 18]. Thus, the species living on and around ice-related landforms can be defined as cryophilous (which means "loving the ice") or cold-adapted species. Among these, the best adapted to survive such extreme habitats are ground beetles (carabids) and non-biting midges (chironomids).

3. Ground beetles and non-biting midges as flagship organisms: richness and adaptation

Ground beetles (**Figure 1**) occur in almost all terrestrial environments and geographical areas and have different trophic requirements (e.g., predators, seed eaters and phytophagous), it is easy to collect them and their sensitivity to environmental and climate changes is known [19]. In addition, they can be considered among the most important meso- and macrofauna living on recently deglaciated terrains and on the glaciers in terms of species richness and abundance of individuals [13]. Last but not least, there is an ongoing awareness about the extinction risk for some endemic cryophilous species due to the habitat destruction (e.g., glacier

Figure 1.
The ground beetle Nebria germari *(approx. body length = 1 cm) walking on the Presena Glacier (2700 m a.s.l.) (Adamello-Presanella Mts., Italian Alps) (photo by F. Pupin/archive MUSE).*

disappearing) or changes in microhabitat conditions (e.g., permafrost melt). Most of the species living at high altitudes and latitudes have low dispersal abilities due to the lack of wings and are walking colonizers, ground hunters and small-sized, which are traits typical of species living in cold, wet and gravelly habitats [17]. To date, about 40,000 species are known in the world [20] and most of them are endemic to specific areas [21–23]; for instance, about 28% of the total species belonging to the Italian carabid fauna are endemic.

Non-biting midges (**Figure 2**) are the freshwater insect family that comprises the highest number of species, both in lentic and lotic habitats [24]. They are the most widespread of all aquatic insect families, with individual species occurring from Antarctica to the equator lands and the Arctic, from lowlands to thousands of meters of altitudes. There are species that thrive in almost every conceivable freshwater environment. Ice-cold glacial trickles, hot springs, thin films, minute containers of water in the leaf axils of plants and the depths of great lakes all have their characteristic species or communities. There are semiaquatic species, living in moist soil or vegetation and others that are truly terrestrial with few species occurring in marine water. Some species tolerate brackish water, others thrive in intertidal pools and, unusually among the insects, and a few are truly marine. Survival in harsh environments is due to a series of adaptations. Among these are the production of melanin, their small size, capacity for mating on the ground instead of in flight (they therefore have small or totally absent wings), the building of cocoons, diapause and resistance to cold [25]. To date, about 6500 species are known in the world; one tenth of which are in Italy and one thousandth in Alpine streams, springs and lakes.

Thanks to their species richness, adaptation to cold environments, key role in the ecological network structure and robustness and sensitivity to short-term and long-term climate changes, ground beetles and non-biting midges might be considered flagship organisms of the glacial biodiversity.

3.1 Ground beetles on glaciers

Clean glaciers and debris-covered glaciers can host permanent populations of ground beetles, at least on the European glaciers since, to our knowledge, there are no data from other extra-European mountain chains. All the species found on the European glaciers belong to the genera *Nebria* and *Oreonebria*. The *Nebria/*

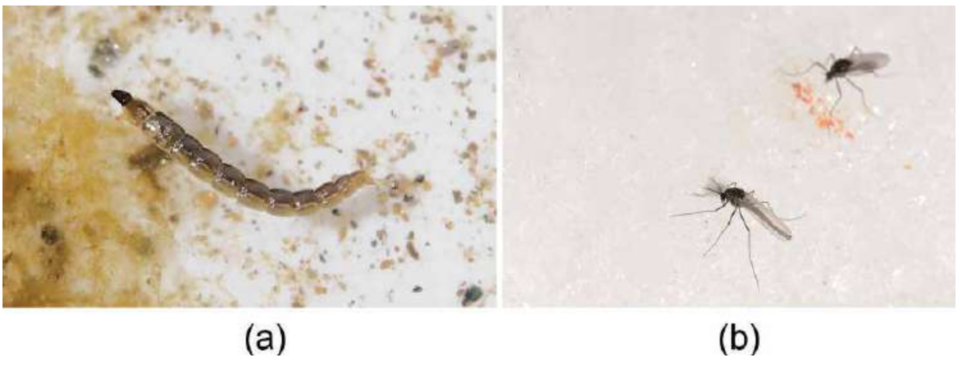

Figure 2.
The non-biting midge Diamesa zernyi *larva (a) from the Amola glacial stream (2540 m a.s.l.) and a couple of adults (male on the left, female on the right) (b) walking on the Presena Glacier (2700 m a.s.l.) (Adamello-Presanella Mts., Italian Alps) (photo by V. Lencioni) (a) and F. Pupin/archive MUSE (b). Animal sizes ca 1 cm.*

Oreonebria species living on clean glaciers are with reduced and not functional wings and wander on the glacier mainly during the night searching for preys (mainly springtails, spiders, non-biting midges and died insects). During the day, they find refuge under the rocks on glacier surface and within the moraines. Their legs are longer with respect to those closely-related species living at lower altitudes and in different habitats, in order to maintain the body to a higher distance from the frozen ground [26].

In addition, debris-covered glaciers are able to host permanent population of *Nebria/Oreonebria* species (**Figure 3**). Currently, data are available for five debris-covered glaciers of the Italian Alps [17, 18, 27, 28].

Nebria/Oreonebria are olfactory-tactile predators; it means that they use the chemoreceptors located on the antenna as instrument to find preys on the glacier surface or between the stony debris. Therefore, these organisms are well adapted to move between the stony debris covering the glaciers, thus across a three-dimensional space. The sex ratio on the glacier is female-biased [29], and the colonization of the glacier from the neighboring habitat seems be done by females that have a higher propensity to disperse than males [29].

3.2 Ground beetles along glacier forelands

The gradual melting of glaciers leave in front of them large areas of barren, pristine ground open for colonization of various life forms. Among these, ground beetles can be found along the entire glacier foreland. Ground beetles can colonize entire glacier forelands, from sites deglaciated since more than one-hundred years to sites deglaciated since one year (**Figure 4**).

The colonization of a glacier foreland by ground beetles is triggered mainly by time since glaciation, distance to glacier and vegetation cover, as highlighted by studies carried out in Northern Europe (e.g., [30–32]), Alps (e.g., [27, 33–36]) and more recently Andes [37]. The colonization of a glacier foreland by ground beetles can follow two different models: the "addition and persistence" and "replacement-change" models [31]. The former was mainly observed in Northern-Europe and on Andes [31, 37], with an exception in the peripheral mountain range of the Southern Alps [38]. It consists in the persistence of pioneer species (i.e., the initial colonizers, e.g., *Nebria* spp. in Europe; *Dyscolus* spp. on the Andes [37]) from the sites deglaciated few years ago (early successional stages) to sites deglaciated more than 100 years ago (late successional stages)—in this case, there is no species turnover along the chronosequence of glacier retreat. The "replacement-change" model, mainly observed on the Alps (e.g., [17, 36]), consists in a group of initial colonizers (the pioneer community) progressively replaced over time by one or more other species assemblages; thus, in this case, there is a clear species turnover. Notwithstanding these different models of colonization, Northern Europe and Alps share ground beetles belonging to common genera and exhibiting the same patterns of colonization. For instance, the species belonging to the genus *Nebria* are surface active predators able to immediately colonize deglaciated terrains of the European glacier forelands. The species belonging to the genus *Amara* and *Carabus*, the former omnivorous and the latter specialized predators, arrived on a deglaciated terrain after more than 20 years [30, 33]. A quite common pattern observed along the European glacier forelands is that the number of species increases with the time since deglaciation, with a more diversified community on terrains deglaciated 100 years ago.

The speed of colonization along the glacier forelands varies with the time since deglaciation. Specifically it is high in the first years after the glacier retire due to the low competition in colonizing pristine terrains, while it is low in terrains located far from the glacier front because more competitive in terms of microhabitat and resource availability [35]. In the contest of the ongoing climate warming, it is interesting to highlight that an increase of 0.6°C in summer temperatures approximately doubled the speed of initial colonization, whereas later successional stages were less sensitive to climate change [39].

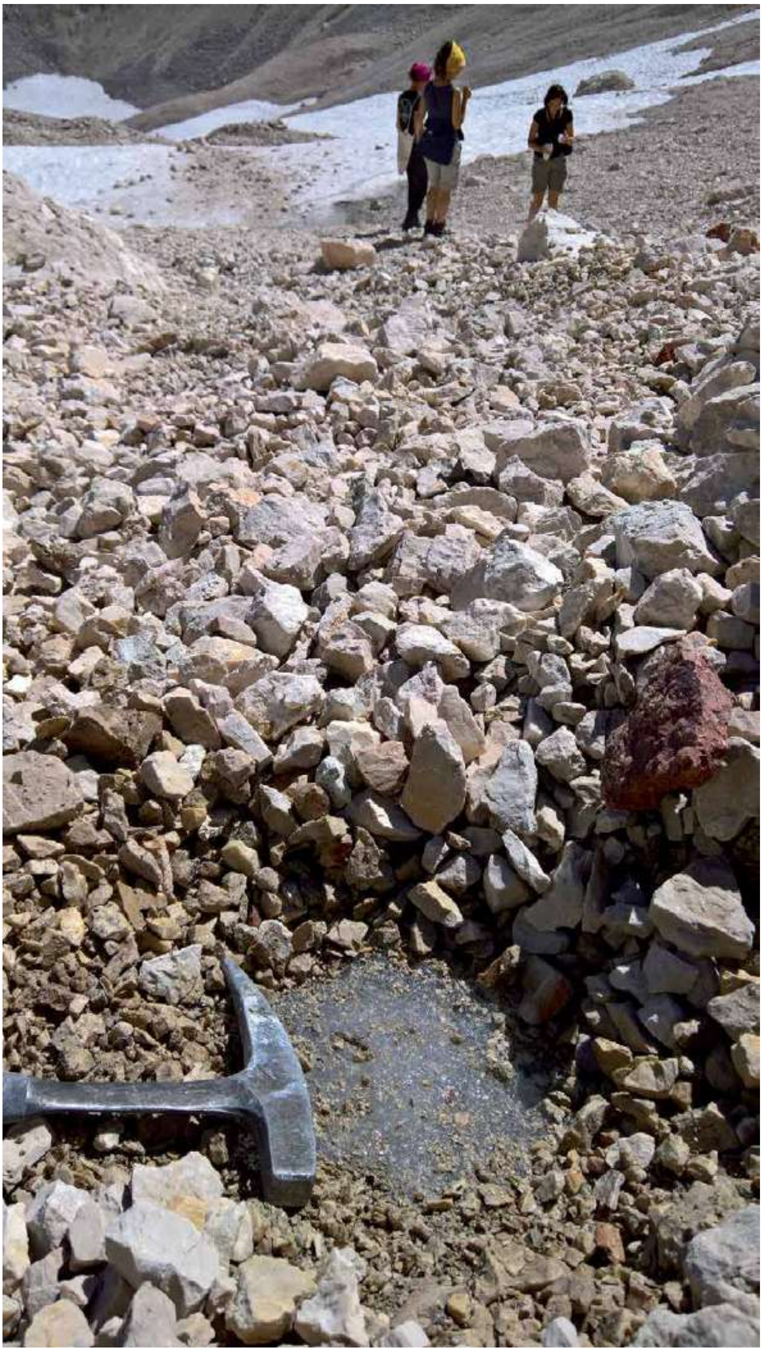

Figure 3.
Stony debris covering the surface of the Sorapiss Centrale glacier (45°N, 12°E, Ampezzo Dolomites, Italian Alps); it hosts permanent populations of cold-adapted ground beetles, spiders and springtails (photo by M. Gobbi).

Figure 4.
Pitfall trap near the front of the Agola Glacier (46°N, 10°E, Brenta Dolomites, Italy). Pitfall trapping is one of the most successful methods to collect ground-dwelling invertebrates at high altitudes during the snow free period (photo by M. Gobbi).

3.3 Ground beetles on rock glaciers

Currently, data on ground beetles found on rock glaciers are available only for the Italian Alps [16, 40 41]. Active rock glaciers are a unique landform: the occurrence of permafrost and the size of the stones differentiate them from the surrounding landforms (e.g., scree slopes) in terms of temperature regime and depth of the substrate. Active rock glaciers show occurrences of cold-adapted species. Even though ground beetle communities of active rock glaciers show few differences in terms of species richness and abundance with respect to scree slopes, some characteristic species of each of the two landforms can be identified. The ground beetle community observed on the rock glaciers is exclusive of this landform because it is composed of large populations of species belonging to the genera *Oreonebria*, *Nebria* and *Trechus* [16, 40]. To these genera belong species (e.g., *Nebria germari*, *Oreonebria soror* and *Trechus tristiculus*) typical of cold and wet high-altitude environments. These species have two kinds of life style: epigeic (they move on the surface of the rock glacier where the rocky detritus is fine) and endogeic (they reach the depth of the stony detritus moving between the interstitial space between stones). Conversely, the surrounding ice-free landforms (e.g., scree slopes) host species assemblages characterized by the presence of species typical of alpine grasslands (e.g., *Carabus* spp. and *Cymindis vaporariorum*). Therefore, an active rock glacier can be defined as a superficial subterranean habitat [16] represented by fissure network among boulders, human-sized caves included.

Unlike other superficial subterranean habitats like scree slopes, where temperatures could reach relatively high values in summer [16, 42], rock glaciers are selected by cold-adapted species, which avoid scree slopes as they do not offer constantly low temperatures during summer.

3.4 Non-biting midges on the glacier

To our knowledge, the only aquatic insects found permanently colonizing the ice are non-biting midges of the genus *Diamesa* in temperate zones and the stonefly *Andiperla willinki* (family Gripopterygiidae) in South America [43]. Larvae of *Diamesa steinboecki* and *Diamesa latitarsis* were collected on one Alpine glacier (2625–2650 m a.s.l., Agola, Brenta Dolomites, Italy), surviving a summer temperature ranging for 0.07 to 0.19°C. Larvae of *Diamesa* were collected also on Yala glacier (5100–5700 m a.s.l., Nepal, Himalayas [44, 45]), growing in melt-water drainage channels under the ice and feeding on blue-green algae and bacteria. They eat the scares allochthonous detritus transported by the wind and left by the glacier in the ice melt waters. Typically, primary food resources in eukryal consist of dust (allochthonous particles or airborne detritus) and algae (various species of cyanophytes and green algae), and fungi and bacteria associated with algae and detritus [46]. Adults were brachypterous (characterized by reduced wings), unable to fly, walking at temperatures as low as −16°C on the surface of the glacier and in small cavities beneath it.

3.5 Non-biting midges in proglacial ponds

Non-biting midges are first colonizers of ephemeral ponds in the proximity of glacier snout. The appearance of new ponds is usually followed by their rapid disappearance and by a concomitant appearance of new ones, frequently observed in the Alps above the tree line [47]. Most of them are relatively small (surface <2 ha) [48], unproductive due to their sparse soil development and small catchments. Ponds are especially susceptible to the effects of climatic changes because of their relatively low water volumes and high surface area-to-depth ratios. Therefore, they act as early indicators of the impacts of climate change. During the ice-free months, typically, they undergo high-level fluctuations due to ice-snow melt rate and rainfall pattern. In winter, they freeze, totally if shallow [48]. Water temperature can be highly variable as well, ranging from 0 to 15°C during summer.

The zoobenthic community of Alpine proglacial ponds is dominated by chironomid Orthocladiinae (generally representing >70% of the community) followed by Diamesinae (*Pseudokiefferiella parva* and *Diamesa* spp.). Aquatic beetles (e.g., Elmidae, Dytiscidae and Hydrophilidae), Oligochaeta (e.g., Enchytraeidae) and Hydracarina frequently represent the remaining fauna. Overall, the richness is low, with few dozens of species colonizing the same pond. Few taxa might be found with high density, up to >1000 individuals/m^2 in ponds >2 ha and less than 2 m deep. Among orthoclads, semiterrestrial genera are frequent (e.g., *Metriocnemus*, *Smittia* and *Parasmittia*), being environments that undergo high water level fluctuations during the ice-free period [49] (**Figure 5**). There are evidence of colonization by up to 4–5 congeneric species of *Metriocnemus* in

Figure 5.
Catching Metriocnemus *adults (non-biting midges) with tweezers on the shoreline of the Agola proglacial pond (2596 m a.s.l., 46°N, 10°E, Brenta Dolomites Mts., Italian Alps) (photo by D. Debiasi/archive MUSE).*

single Alpine ponds (Agola glacier, 2596 m a.s.l., Brenta Dolomites, Italy), with *M. fuscipes* and *M. eurynotus* as dominant species. The genus is considered semiterrestrial, found in mosses, phytotelmata, springs, ditches, streams and occasionally in the middle of lakes and rock pools [50]. Some ability to survive desiccation and hibernation often in combination with cocoon building and migration of larvae into the sediment [51] has been recorded for several *Metriocnemus* species dwelling in ephemeral habitats that seasonally dry or freeze out. The colonization of these ponds by *Metriocnemus* might be due more to these physiological adaptations than to repeated recolonization as observed for other chironomids colonizing ephemeral ponds [52]. In fact, due to the high geographical isolation of the pond and scarce connectivity with other suitable habitats in the catchment, we can suppose that these species persist by activating a physiological response to physical stress. Most of these species are univoltine, entering diapause in a desiccated-frozen state until spring thawing.

3.6 Non-biting midges in glacier-fed streams

Non-biting midges are the main colonizers of glacier-fed streams around the world. Glacially dominated rivers are characterized by a deterministic nature of benthic communities due to the overriding conditions of low water temperature, low channel stability, low food availability and strong daily discharge fluctuations associated to glacier runoff (**Figure 6**). A predictable longitudinal pattern of taxa richness and diversity increasing with distance from the glacier has been described for many European glacier-fed streams, starting from the kryal sector (where maximum water temperature is below 4°C), typically colonized almost exclusively by *Diamesa* species in the temperate regions [53]. *D. steinboecki*, *D. goetghebueri*, *D. tonsa*, *D. zernyi* and *D. bohemani* are the species more frequent and abundant in kryal sites in the Palearctic regions, followed by *D. bertrami*, *D. latitarsis*, *D. modesta*, *D. hamaticornis* and *D. cinerella*. Less frequent are *D. martae*, *D. nowickiana*, *D. longipes*, *D. wuelkeri* and *D. aberrata*; *D. insignipes*, *D. dampfi*, *D. permacra* and

Figure 6.
Dubani glacial stream at the glacier snout (3232 m a.s.l., 36°N, 74°E; Bagrote Valley, Karakoram range of northern Pakistan) (photo by L. Latella).

D. incallida are rare, being more frequent in glacio-rhithral and krenal habitats, characterized by a lower glacial influence. *D. arctica* is typical of the Arctic regions, and *D. akhrorovi*, *D. alibaevae*, *D. planistyla, D. solhoyi*, *D. aculeate*, *D. praecipua* and *D. khumbugelida* are among the *Diamesa* species typical of Pamir and Tibet mountains. In tropical streams, mainly Podonominae colonize the uppermost glacier-fed stream reaches, while Diamesinae appear more downstream [54]. In glacier-fed streams of New Zealand, [55] reported the mayflies (Ephemeroptera) *Deleatidium cornutum* and *Nesameletus* dominated at the upper sites of glacier-fed streams, with the chironomids *Eukiefferiella* and *Maoridiamesa*. Biodiversity naturally increases with decreasing altitude and increasing distance from the glacier terminus, with a more diversified community downstream of the confluence with tributaries fed by groundwater and rainfall (= krenal and kreno-rhithral). Orthocladiinae and Tanypodinae (e.g., *Zavrelimyia*) become more abundant, followed by Tanytarsini (e.g., *Micropsectra* spp.) in slow-flowing waters where mosses are abundant.

4. Threats and opportunities for ground beetles and non-biting midges in relation to climate warming

Glaciers and permafrost are disappearing all over the world, and with them, we are risking to lose also the associated glacial biodiversity. Therefore, it is mandatory to describe the temporal and spatial biological fingerprint of climate change impacts to deeply understand trends and patterns.

The available literature on ground beetles and non-biting midges is able to give us insights about the threats and opportunities they have in relation to the ongoing climate and, consequently, landscape changes.

4.1 Extinction

Currently, no ground beetles living on glacial and periglacial landforms have been declared extinct. On the other hand, the temporal reduction in population size of two high-altitude species (*Nebria germari* and *Trechus dolomitanus*) of the Dolomites (Italy) in 30 years was documented [56]. Specifically, local extinction of *Nebria germari* populations was documented in some high-altitude prairies of the Dolomites, and now the species maintain large populations only on glacial and periglacial landforms; thus, it has become an ice-related species.

As observed for ground beetles, also for non-biting midges from kryal habitats, there is no evidence of global extinction of single species, rather of local extinction caused by the retreat of glaciers. The consequence of the glacial retreat is the further isolation of the populations in the short-term and, in the long-term, their possible disappearance due to very restricted habitat preference and limited dispersal abilities of midges. Glacier shrinking favors an upstream shift of lowland euriecious species of chironomid and other invertebrates, associated with an initial decrease in abundance and finally local extinction of kryal *Diamesa* species and other Diamesinae [57]. *Diamesa longipes* and *Syndiamesa nigra* have not been collected in recent years in Alpine running water [53], and the ice fly *Diamesa steinboecki* has disappeared in some glacier-fed streams in the Southern Alps [58]. The strong cold hardiness of *Diamesa* species [59] and the scarcity of potential refuge areas in glacial and periglacial area threaten these species seriously with extinction. Thus, *Diamesa* species have been suggested to be used as sentinels for climate change, especially in relation to glacier retreat. Recent studies found a direct relationship between the loss of *Diamesa* species in alpine riverine environments and the consequences of the changing climate [58].

4.2 Uphill and upstream shift

Higher temperatures and increased drought are leading to an upward shift of stenothermal species that depend on low temperatures and therefore to the fragmentation and progressive reduction in their habitat. Any endemic species, like several high-altitude ground beetles, that is restricted to summit areas and has a low dispersion ability is forced to move upward searching for microclimates suitable for its survivor. Data on ground beetles resampled in the same places after decades suggest common trend in cryophilous species. For instance, on the Andes, from 1880 to 1985, the species *Dyscolus diopsis* has shifted approximately 300 m upward, with the resulting area reduction of more than 90% from >12 km^2 to <1 km^2 [60]. The same altitudinal shift was observed on the Dolomites for the species *Nebria germari* [27] from 1950 to 2019; the habitat preference for this species was alpine prairies [61], N-exposed scree slopes and recently deglaciated terrains, and currently, it seems to be restricted only to ice-related landforms and scree slopes with high snow cover temporal extent.

Shrinking glaciers are resulting in the lengthening of glacial streams, with consequent upstream migration of specialist species to colonize the "new" stream reach, still harsh, in front of the glacier terminus. Downstream generalist species also migrate upstream, to conquer sites with ameliorated environmental conditions associated to a reduced glacial runoff and increased temperature and channel stability [62, 63]. For example, in the Alps, as first colonizers upstream were observed grazer (chironomid Orthocladiinae among which *Eukiefferiella* spp., *Heleniella* spp., *Orthocladius frigidus* and *Chaetocladius* spp.) and shredder insects (Nemouridae), covering distances from 300 m to about 2 km and a difference in altitude up to 600 m probably favored by higher amount of debris from the banks [58].

4.3 Adaptation

To the best of our knowledge, there is no evidence of physiological or morphological adaptation of carabid beetles in relation to the climate change at high altitudes, and it seems that limits to species distributions reflect present environmental tolerance limits rather than simply an historical lack of opportunity for range expansion [64]. Some studies on thermal tolerance highlighted that temperature gradients and acute thermal tolerance do not support the hypothesis that physiological constraints drive species turnover with elevation [65].

Cold stenothermal non-biting midges that adapted to live at temperatures close to their physiological limits like *Diamesa* spp. might only survive and reproduce if they can adapt to new environmental conditions or if they are able to avoid the stressor adopting specific behaviors. Barring these abilities, they are expected to disappear. There are evidences of physiological adaptation in Diamesinae to increasing water temperature in glacier-fed streams. For example, *Diamesa zernyi*, *Diamesa tonsa* and *Pseudodiamesa branickii* are cold hardy with a thermal optimum below 6°C but survive short-term heat shock by developing a heat shock response based on the synthesis of heat shock proteins [66]. It is clearly not sufficient to preserve the species considering the observed cases of local extinction. Decreasing glacier cover disadvantages Diamesinae and other cold stenothermal taxa but favors organisms with long life cycles (univoltine) or more (semivoltine) due to continuous growth around the year (life cycle shifts suggest that where glacier cover is high, nondiapausal organisms typically develop rapidly in the spring/summer melt seasons before rivers dry up or freeze through winter) [67]. Furthermore, decreasing glacier cover favors insects that undergo incomplete metamorphosis, such as Plecoptera (stoneflies) and Ephemeroptera (mayflies), and noninsect taxa such as Oligochaeta (worms), burrowing and using interstitial habitat. Dietary shifts reflect terrestrial vegetation succession with decreasing glacier cover supplying plant litter to rivers resulting in higher amount of organic material for detritivores. These shifts were observed in glacialized systems in European Alps (Austria and Italy), French Pyrénées, Greenland, Iceland, New Zealand Alps, Norway Western Fjords, US Rockies, Alaska and Svalbard [67].

4.4 Refuge areas

If the speed of adaptive capacity—when possible—is not temporally synchronous with the speed of the glacier retreat, the only way to survive for cryophilous species is to find refuge areas. A refuge can be defined as sites able to preserve suitable climate conditions for cold-adapted species in spite of the climate warming [68]. The role of active rock glaciers and debris-covered glaciers as potential warm-stage refugia for cold-adapted ground beetle species is supported by data collected on the Italian Alps [16, 28, 40]. The thermal profile observed on some alpine active rock glaciers supports this view indicating decoupling of the local topoclimate from the regional climate, a key factor for a site to serve as a refugium. Specifically, active rock glaciers differ from the surrounding landforms (e.g., scree slopes) by overall lower ground surface temperature (average annual temperatures around or below 0°C). During postglacial periods, cold-adapted species found refuge in cooler habitats, such as subterranean environments (e.g., caves), where they could find cold and stable microclimatic conditions [69]. Thus, we cannot exclude that the same pattern is acting till now for ground beetles on active rock glaciers and debris-covered glaciers, because only these landforms are still able to support large-size populations of cold-adapted species.

In streams, the majority of invertebrates avoid the hazards of freezing or desiccation (due to freezing of the substrate or due to drought caused by increasing temperature) by migrating to unfrozen habitats (e.g., springs fed by groundwater inputs and hyporheic zone), where they remain active [70]. This is a temporary adaptation, to escape daily or seasonal risk of freezing or desiccation. On long time scale, these refugia cannot preserve cold stenothermal *Diamesa steinboecki* and similar species, never found in springs and not confined to the hyporheic having the terrestrial adult. Rock glacier outflows might act as a cold refuge areas after the glacier loss also for aquatic insects due to their constantly cold waters [71]. Ref. [72] investigated five streams fed by rock glaciers in South Tyrol (Italy) and found a dominance of Diamesinae and Orthocladiinae chironomids, besides Plecoptera, Ephemeroptera and Trichoptera (EPT). The authors reported the presence of cold-stenothermal species (*Diamesa* spp.), which suggests that rock glacial streams can act as refuge areas after the glacier loss [73]. However, further studies are necessary to demonstrate that cold-hardy *D. steinboecki* and other *Diamesa* species restricted to kryal habitat might survive competition with spring fauna (EPT) in rock glacier outflows.

4.5 Chemical pollution

Among the stressors that threaten the glacial biodiversity, there are also chemicals, i.e., persistent organics pollutants (POPs) deriving from long-range atmospheric transport and pesticides and emerging contaminants (e.g., personal care products as fragrances and polybrominated diphenyl ethers (PBDEs) widely used as flame retardants) carried to the glaciers by short-medium range atmospheric transport. These pollutants undergo cold condensation and accumulate in the glacier ice until their release in melt waters and ice-free soil [74, 75].

Among organic contaminants detected in glacier-fed streams, attention was paid to the insecticide chlorpyrifos, since high toxicity to insects and peak release by glacier melting occur concurrently with the period in which the streams are more densely populated by macroinvertebrates [76]. Chlorpyrifos and other organophosphate insecticides are known to exhibit increased toxicity in invertebrates at elevated temperatures [77]. Specifically, warming influences chlorpyrifos uptake in aquatic insects magnifying its negative effect on fauna. Other contaminants are heavy metals released by remains of the Great War, such as bombs, bullets, cannon parts and barbed wire buried in the ice 100 years ago, that are emerging due to glaciers retreating. These new sources of contamination have been recently documented for ice melt waters in the Italian Alps (mainly by nickel, arsenic and lead, unpublished data). Contamination of soils of the 1914–1918 Western Front zone, in Belgium and France by copper, lead and zinc was previously detected by [78]. Pesticides, fragrances and heavy metals affect swimming behavior and metabolism of *Diamesa* species from glacier-fed streams [79] at trace concentration (in order of ng/L), with still unknown effects on aquatic food web and on terrestrial fauna (*via* food web). To our knowledge, the understanding of final environmental fate of such pollutants is still scarce and fragmentary. Recently, evidences of microplastic bioaccumulation are given for freshwater amphipods from Svalbard glacier-fed streams [80] and for *Diamesa zernyi* larvae from the Amola Glacier-fed stream (Italy). No information is now available on their effects on ground beetle fauna.

5. Role of glacial biodiversity in the glacial-ecosystem functioning and services

Given the global change scenarios, it is opportune to analyze the role of glaciated areas in the context of persistent change from the physiographic point of view as well as the glacial biodiversity they host.

Standardized long-term monitoring, additional high-quality empirical studies on key organisms and landforms, and further development of analytical methods are of extreme importance in helping to quantify the extinction debt better and to more successfully enhance and protect glacial biodiversity.

Glacier shrinkage will alter hydrological regimes, sediment transport, and biogeochemical and contaminant fluxes from rivers to oceans, which will profoundly influence the natural environment and the ecosystem services that glacier-fed rivers provide to humans, particularly provision of water for agriculture, hydropower and consumption [4]. Biodiversity influences ecosystem functioning through changes in the amount of resource use or water self-depuration processes (regulating services) but is also a source of scientific and tourist attraction (cultural service).

Glacial biodiversity has an intrinsic value; most of the species are highly specialized to live in harsh environments, thus highly vulnerable to changes also of low intensity, have low dispersal ability and in most of the glacialized area of the world are endemic. Therefore, glaciated areas become territories with a collection of communities and species that mostly differ from those dominant in middle and low altitudes as well as differ between geographic areas. In addition, insects and other arthropods (e.g., spiders) living on the moraines, on the glaciers or flying on the glaciers (e.g., chironomids and stoneflies) act as additional source of food for some high-altitude mammals and bird species living at the edge of ice-related landforms [81, 82]. Therefore, glacial biodiversity is able to furnish an additional important naturalistic value of glacialized mountain regions.

Aquatic and terrestrial insects living in glacialized areas are trophically connected [83, 84], but not all insect groups react in the same way to the ongoing glacier retreat. Increasing glacial retreat differently affects ground-dwelling and aquatic insect taxa: ground beetles respond faster to glacier retreat than do non-biting midges, at least in species richness and species turnover patterns [84]. It depends on how fast habitat conditions change in relation to glacier retreat: the terrestrial environment changes faster than the aquatic environment. For instance, an increase of 0.6°C in summer temperatures approximately doubled the speed of colonization of the recently deglaciated terrains by ground-dwelling invertebrates [39]. The glacial stream lengthens but the physicochemical features and hydrological regime may not change for a long time, until the surface of the glacier is reduced to a few hectares and finally the environment becomes less extreme for life. As a result, as long as the environmental conditions remain extreme, the community in the glacier-fed stream is not affected.

Because even small ecosystem fragments like glaciers or other ice-related landforms have conservation value for insect biodiversity and ecosystem services, a better understanding and delineation of the species that need to be protected is also important. Funding of long-term research activities on habitat conservation in general, and specifically on insect science and taxonomy, is especially important to evaluate and mitigate future changes in insect communities, obtain reliable insect time series and discover species before they go extinct.

6. Conclusions

A recent large-scale study aimed to investigate trends in insect abundances over space and time has brought evidences about an average decline of terrestrial insect abundance (ca. 9%) per decade and an increase of freshwater insect abundance (ca. 11%) per decade. Both patterns were particularly strong in North America and some European regions [85], and the hypothesized drivers are land-use change and climate change.

Ground beetles and non-biting midges are among the animals best adapted to live at high altitudes, specifically to colonize the glaciers and surrounding terrestrial and aquatic habitats. They are present with few species adapted to low temperatures and food scarcity, factors that make these habitats extreme for life.

Spatio-temporal shift in insect communities in relation to the ongoing climate change is one of the most common patterns in mountain regions, but it is important to highlight that it will not affect all species equally [85, 86]. Aquatic and terrestrial insect communities seem to be differently affected by climate change. Firstly, because temperature variability is stronger on the ground with respect to water, aquatic insects are required to make smaller behavioral or physiological adjustments than terrestrial insects and aquatic habitats will be more buffered from climate warming [86]. In addition, terrestrial insects may have wider opportunities to survive in appropriate microclimate colonizing or surviving in ice-related microhabitat, thanks to the higher microhabitat heterogeneity on the ground with respect to the aquatic habitat.

The chapter provides a synthesis about the fascinating adaptations in morphology, behavior and physiology in terrestrial and aquatic species, on the species distribution in relation to the ice-related landform heterogeneity and on which species are threatened with extinction due to climate change and pollution. The future challenge will be to try to improve the knowledge of the glacial biodiversity in high-altitude and high-latitude areas notwithstanding the difficulty of accessing most of these areas.

Three research goals should be addressed in the near future: (i) increase the studies aimed at describing the glacial biodiversity; (ii) plan long-term monitoring projects in key areas and (iii) improve the scientific communication about the threats on high-altitude habitats. Thus, with this chapter, we are confident to inspire young researches to investigate the life in glacial ecosystems of the world before its possible disappearance.

Acknowledgements

We are grateful to the several colleagues and students that since more than 20 years are cooperating with us in collecting ground beetles and non-biting midges in glacialized areas of the world. We are also thankful to the National and Natural Parks that allowed the permission to monitor the insect populations of the glacial and periglacial environments.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 9

Variations of Lys Glacier (Monte Rosa Massif, Italy) from the Little Ice Age to the Present from Historical and Remote Sensing Datasets

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Abstract

Alpine glaciers respond to climate imbalance by adjusting their mass and length. In turn, these changes modify the glacial and periglacial environment, leading to increased supraglacial debris cover, the development of glacial lakes and glacier fragmentation. In this research, we investigated the evolution of Lys Glacier (Monte Rosa Group), by studying length, area and volume changes, and evolution of its supraglacial debris cover and proglacial lakes by means of historical sources and high-resolution aerial and satellite orthophotos. Lys Glacier retreated almost continuously, by nearly 2 km, from its maximum Little Ice Age position. More recently, the glacier lost 11.91% of its area between 1975 and 2014 and underwent fragmentation in 2009. Over the same period, glacier fragmentation and tongue stagnation affected the formation and rapid growth of a series of ice-contact lakes and led to a non-linear debris cover evolution. The glacier was also subjected to strong volume losses, with more than 135 m thinning on the ablation tongue from 1991 to 2014. Analysis of the meteorological records (1927–present) from the closest weather station reveals a considerable increase in average annual temperatures by more than 1°C from the mean of 1971–1989 to the mean of 1990–2017.

Keywords: alpine glacier, terminus fluctuations, area change, volume change, debris cover, glacial lakes

1. Introduction

Observations show that the strongest influence of global climate change is recorded in alpine environments and glaciers are the first to be affected by global warming [1]. The response of a glacier to climate imbalance occurs initially through mass loss; eventually, the glacier adjusts to mass changes by changing its geometry, including area and length [2]. These geometric changes are also often accompanied by a shift in the glacier geomorphology, including an increase in the glacier debris cover, which can then decouple the glacier response from the temperature signal, and the appearance of thermokarst features such as kettles and ice-contact lakes [3], with possible impacts on glacier hazards downstream [4]. In fact, debris-covered glaciers and the expansion of supraglacial debris cover on debris-free glaciers are increasingly prominent features of the world's glaciated catchments in mountain regions including Himalaya [5], Karakoram [6, 7], Andes [8], Alps [9], Southern Alps of New Zealand [10], and Caucasus [11].

Over the past century, Italian glaciers have been shrinking at high rates [12–14]. Among these, Lys Glacier, located in the Monte Rosa massif (**Figure 1**), can be considered paradigmatic of the changes affecting alpine glaciers. Its response to increasing temperature and reduced accumulation is in fact similar to that of most glaciers in the Alps and elsewhere [14–17]: terminus retreat, area reduction and decreasing ice thickness. In addition, Lys Glacier has also recently shown other climate-related changes, including detachment of the main debris-covered tongue from the rest of the glacier body and possible separation of the two branches of the glacier tongue (**Figure 1a**); variations in supraglacial debris cover (both surface and thickness) on the glacier tongue, thermokarst features (e.g. kettle ponds) and processes (**Figure 1b**); and calving processes at the terminus where an ice-contact lake developed in the late 1990s (**Figure 1c**).

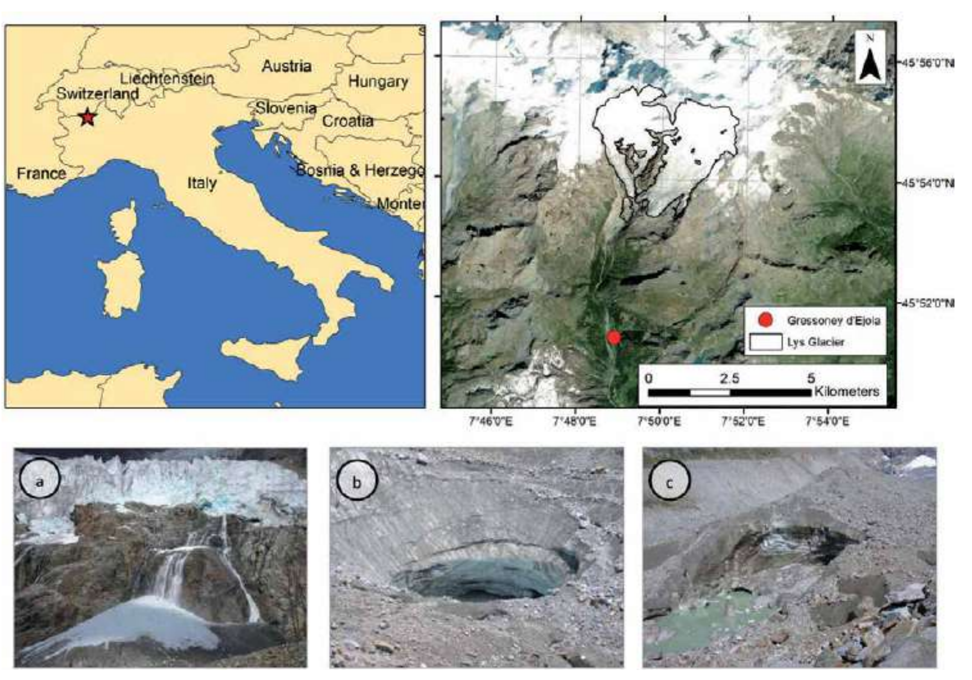

Figure 1.
Location of Lys glacier within Italy (red star) and of the weather station used in this study (red dot). The bottom pictures show some typical features found on the glacier tongue in recent years, including (a) separation of two tributaries from the main debris-covered tongue; (b) thermokarst features and processes; (c) calving processes at the ice-contact lake.

In the current context of temperature warming and glacier regression, long-term data reporting changes in glacier properties represent an important asset, as terminus, area and volume fluctuations can provide important information concerning the response of a glacier to climate imbalance. These data are a fundamental input for models that enable reconstructing past climate (from terminus fluctuations [18, 19]) and projecting future glacier changes [20], the availability of meltwater for domestic use and the production of hydroelectric energy [21, 22], as well as the formation of future lakes and potential hazards [23] and the impact of glacier change on tourism [24].

In this study, to describe the evolution of Lys Glacier, a multiple approach was followed. Terminus fluctuations since the early nineteenth century were analyzed using a variety of sources including detailed bulletins with reports of glaciological campaigns; over a more recent period (1975–2014), the area changes of the glacier were estimated by using remote sensing datasets, i.e. satellite and aerial orthophotos, while volume changes were evaluated by comparing a pair of digital elevation models (DEMs) obtained from cartography and satellite images. In addition, these sources permitted us to evaluate the evolution (i.e. surface cover and patterns) of the supraglacial debris cover and of the ice-contact lakes over the same period of observation and gain insights into the geomorphological evolution of the glacier.

2. Study site

Lys Glacier drains the southern flank of the Mont Rosa Group (45°54’ N, 07°50′ E) (**Figure 1**). The most recent Italian glacier inventory ([14], data from 2005) reports a glacier area of 9.58 km^2, a south westerly aspect, an elevation range between 2392 and 4323 m a.s.l. and a length of 5.71 km. While Lys Glacier is presently the fourth largest Italian glacier, comparatively few studies have been conducted to investigate its evolution over the past century and recent decades. Strada [25] described terminus fluctuations until the early 1980s; Pelfini et al. [26] estimated the glacier response time using dendrochronology; Rota et al. [27] used DEMs from cartographic sources to calculate volume changes between 1925 and 1994. None of these studies or iconographic sources show evidence of continuous supraglacial debris cover until the late 1980s. Since then, debris cover has been present on the lower sector of the ablation tongue, initially as the continuation of medial moraines at an elevation below 2550 m a.s.l. The medial moraines formed below the glacier icefalls (**Figure 2**), thanks to the debris supplied by the surrounding deglaciated rock walls (owing to macrogelivation processes, permafrost degradation and structural rock falls). In more recent years, debris has come to cover the entire glacier tongue below 2550 m a.s.l., until its detachment from the upper sector of the glacier, which occurred in 2009 [28]. The occurrence of debris cover is thus a recent phenomenon and probably a consequence of the present deglaciation, which has affected Lys Glacier as well as the other alpine glaciers [1, 15]. Although Lys Glacier cannot be considered a debris-covered glacier even in recent times (as only a small sector of the glacier surface is continuously debris-covered, see [29]), the supraglacial morphologies and the processes affecting the debris-covered glacier tongue are comparable to those of larger debris-covered glaciers in Asia and in the Alps, including thermokarst processes and the formation of cavities and ice-contact lakes [29].

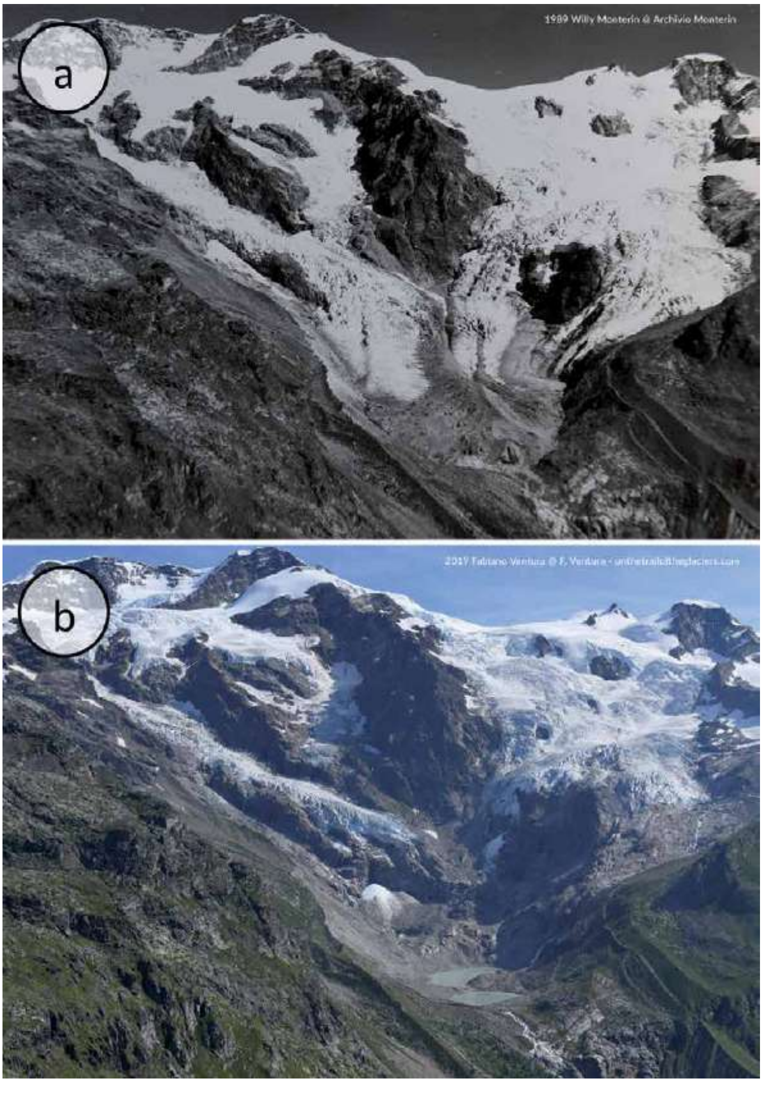

Figure 2.
Comparison of historical photographs of Lys glacier. (a) 1989. The glacier exhibits medial moraines on the distal part of its tongue, which is well developed. (b) 2019. The glacier has retreated above a rock wall in the western sector, leaving a dead ice tongue underneath, with a proglacial lake developing in the depression left by the disappearing tongue. The moraine ridges from the 1980s advance phase are also evident. (photo credits: (a) Willy Monterin-© Archivio Monterin. (b) Fabiano Ventura-© F. Ventura-sulletraccedeighiacciai.com).

3. Materials and methods

3.1 Terminus fluctuations

In this study, the terminus fluctuations of Lys Glacier were retrieved from different sources; early data concerning the nineteenth century are the same used in Strada [25] and references therein, i.e. early cartographic sources (map of the states of Sardinia from 1818 and cadastral maps), photographs and descriptions, particularly those in Monterin [30]; from the early twentieth century, length changes were obtained by extracting the field measurements available from the journals published by the Italian Glaciological Committee (CGI) [31, 32]. Surveys of the glacier terminus positions consist of tape measurements from fixed reference points in the glacier forefield, made at or near the end of the balance year, i.e. in the autumn season, with an estimated accuracy about 0.5 m, which can become worse in case of bad environmental conditions, poorly documented switches to new reference points, measurements taken over very long distances or at points on the snout outside the main flow line, or residual snow patches [12]. While the actual uncertainty from these issues is difficult to quantify, glacier terminus fluctuations remain an important asset to assess global climate and environmental change [19].

We followed recommendations by Citterio et al. [12] to perform quality-checking of the measurements extracted from CGI journals, to minimize the issues related to changing reference points or surveyors over the years. When multiple measurements were available from the same survey, an averaged variation was calculated. In case of missing years in the record, periods up to 5 years where the reference point had remained the same were filled by uniformly distributing the total terminus variation over the missing years.

In case of a gap associated with an undocumented change in a reference point, the gap was not filled, and the first measurement following the gap was considered as the starting point for comparison with the measurement resulting for the following year, as in Citterio et al. [12]. The data record for Lys Glacier from CGI journals is rather uninterrupted and permits analyzing the glacier history in detail over the last century.

3.2 Cartographic analysis

3.2.1 Data sources and preprocessing

Maps, aerial orthophotos and satellite images were analyzed to calculate the area and volume changes of Lys Glacier and changes in the area of the proglacial lakes. The available cartographic sources include large-scale maps from the Val d'Aosta region, produced in 1975 and 1991 at a nominal scale of 1:10000 (**Table 1**). The maps were available in digital form as rasters, projected in the UTM32N coordinate

Remote sensing data	Date	Resolution (m)	Usage
Regional technical map	1975	10	Glacier outlines
Aerial orthophoto	07/09/1988	0.5	Glacier outlines, debris cover mapping
Regional technical map	1991	10	Glacier outlines, DEM production, volume change
Aerial orthophoto	15/06/1994	0.5	Glacier outlines, debris cover mapping
Aerial orthophoto	31/08/1998	0.5	Glacier and lake outlines, debris cover mapping
Aerial orthophoto	12/09/2003	0.5	Glacier and lake outlines
Aerial orthophoto	04/09/2006	0.5	Glacier and lake outlines, debris cover mapping
Aerial orthophoto	16/07/2012	0.5	Glacier and lake outlines, debris cover mapping
Pleiades PHR1B	01/09/2014	2	Glacier outlines, DEM production, volume change, debris cover mapping

Table 1.
List of datasets used in this study and their usage; the acquisition date (whenever available) is reported as dd/mm/yyyy.

system based on the ED50 datum; contour lines and elevation points were digitized as shapefiles, and a DEM was produced from the 1991 map with a pixel spacing of 10 m using ArcMap Topo to Raster utility.

Aerial orthophotos from 1988 to 2012 (**Table 1**) were obtained from Geoportale Nazionale (http://www.pcn.minambiente.it/mattm/); these have a pixel size of 0.5 m and were downloaded in the UTM32 coordinate system based on the WGS84 datum. Most images were acquired in late summer months (August and September; **Table 1**), with minimum snow cover, while the orthophotos from 1988 and 2012 were acquired in early summer (June and July) and show evidence of residual snow, which however does not affect the glacier tongue. In addition to the aerial orthophotos, we obtained a stereo pair acquired from the Pleiades satellite constellation from the European Space Agency. The stereo pair was imaged on 1 September 2014 and provided at level 1B processing stage; we further processed it to obtain a DEM and an orthorectified image using NASA's AMES stereo pipeline (ASP). Eleven ground control points were selected from those available from Val d'Aosta regional authority (http://geonavsct.partout.it/pub/GeoNavITG/monografie.asp) to improve the geolocation accuracy of the DEM through bundle adjustment in the software; the DEM was then produced using the semi-global matching algorithm available in ASP [33], and the raw multispectral images were projected onto the DEM for orthorectification. Both the Pleiades DEM and multispectral image have a final resolution of 2 m.

3.2.2 Calculation of area and volume changes

Based on the available planar data (**Table 1**), the glacier and proglacial lake outlines were estimated over multiple years: in the 1975 and 1991 technical maps, they were already drawn on the map, while in the other datasets, they were manually digitized as part of this study. The spatial resolution of the orthophotos allowed us to clearly identify the outlines and to distinguish the debris-covered parts of the tongue from the proglacial areas. Before digitization, all available data were reprojected to the UTM32N coordinate system based on the WGS84 datum for consistency. We further evaluated the accuracy of the manual delineation using the buffer method proposed by Paul et al. [34], by allowing the glacier and lake outlines to grow and shrink with a buffer of 2 pixels.

The analysis of elevation and volume changes was based on the comparison of the DEMs from 1991 and 2014. Before performing this comparison, the DEMs were co-registered using the approach developed by Berthier et al. [35] and applied by Fugazza et al. [36]. In this approach, one DEM ('slave') is iteratively shifted with respect to a reference DEM ('master'), to minimize the standard deviation of elevation differences over stable areas located outside the glacier ($\sigma_{\Delta h}$). We selected the oldest DEM as the reference and resampled both DEMs to a common resolution of 10 m. By applying the co-registration, we obtained a residual $\sigma_{\Delta h}$ of 4.18 m; the average elevation difference over stable areas was 7 m, which was subtracted from the reference DEM. Based on the elevation difference on the glacier surface, we then calculated the volume change as:

$$\Delta V = \sum_{k=1}^{K} d_k A_k \tag{1}$$

where k = 1 ... K are the pixels of the reference surface, A_k is the area of each pixel and d_k is the pixelwise difference between the 1991 and 2014 DEMs.

To express the uncertainty of volume changes, we used the approach described by Fischer et al. [37]: the uncertainty in elevation change ($\sigma_{\Delta h}$) is not considered as entirely correlated but scaled to account for the effective correlated area A_{cor}, based on the correlation length (i.e. the distance at which two pixels are correlated). We calculated the correlation length using an empirical semivariogram in R software as 200 m and the effective correlated area as 0.12 km^2. The uncertainty in volume change $\sigma_{\Delta h\_cor}$ is then expressed as:

$$\sigma_{\Delta h\_cor} = \sqrt{\sigma^2_{\Delta h} \cdot \frac{A_{cor}}{5 \cdot A_{1991}}} \tag{2}$$

where A_{1991} is the glacier area in 1991. The uncertainty calculation can in our case only be applied to the glacier tongue, as at altitudes above the glacier equilibrium line the presence of snow with little contrast deteriorates DEM reconstruction and leads to larger errors [38], particularly with the oldest DEM from 1991.

3.2.3 Mapping debris cover and its changes

To characterize the evolution of debris cover on Lys Glacier, we adopted the methodology proposed by Azzoni et al. [9] for glaciers in the Ortles-Cevedale Group. Supraglacial debris was mapped by employing a maximum likelihood (ML) supervised classification approach. Four classes were included in the classification: debris, ice, snow and shadow. Although we did not aim at mapping the other surface types, a higher number of classes was chosen to permit an improved mapping of debris cover; the shadow class was also included as some images are affected by topographic shadow; this occurred mostly in the accumulation basins except for the orthophoto from 2003, where shadows occur over the whole glacier; thus, this orthophoto was excluded from the analysis (**Table 1**). We also excluded the maps from 1975 and 1991, as the information on the presence of debris was not available. For each of the satellite/aerial orthophotos, we independently selected 10 to 15 training areas. To estimate the accuracy of the classification approach, we performed a validation test on the 2006 and 2012 orthophotos, by selecting 100 random points for each test and comparing the results of ML classification against those from a manual classification. The 2 years were chosen because they represent best (2006) and worst (2012) conditions for debris cover mapping, in terms of image quality, presence of snow and shadows. For both years, we calculated overall accuracy (the ratio of the number of correctly classified points to the number of total points), as well as producer's accuracy (PA) and user's accuracy (UA), for the different classes. PA denotes the ratio of the number of correctly classified points to the total (manually classified) point for a class and is the complement of omission errors; UA denotes the ratio of the number of correctly classified points to the number of predicted points for a class and is the complement of commission errors.

3.3 Meteorological data

In order to interpret the glaciological data of the study area, we analyzed meteorological variables recorded by the weather station installed in 1927 at Gressoney d'Ejola, 1850 m a.s.l., at a distance of 3.7 km from Lys Glacier (**Figure 1**). This long dataset allows investigating the recent climate behaviour, which influences the evolution of the glacier. At this weather station, manual observations of air temperature, liquid precipitation, total snow depth and thickness of fresh snow, atmospheric pressure, relative humidity, wind speed and velocity and cloud type and cover were collected three times a day (at 8 am, 2 pm and 7 pm) from 1927 to 2012. The data record is almost uninterrupted except for a short period from 1962 to 1970, when the station was temporarily moved downvalley, at 1730 m a.s.l. in the Orsia village. In 2002, an automatic weather station was installed at the same site, and it replaced the manual weather station after its dismissal in 2012. The automatic weather station measures air temperature, total precipitation (by a heated gauge) and snow height (by an automatic webcam) every hour. The contemporary presence of manual and automatic instruments has allowed ensuring the homogeneity and continuity of the series. Although a weather station also exists at a higher elevation and closer proximity to Lys Glacier (Alpe Courtlys, 1992 m a.s.l., 2.5 km distance), this station was installed in 2001 and does not permit a long-term analysis of climate variables. In this study, we calculated monthly, seasonal and annual averages of air temperatures and monthly, seasonal and annual cumulated liquid/solid precipitation for the analysis of climatological conditions.

4. Results

4.1 Terminus fluctuations

The history of the advances and retreats of Lys Glacier is summarized in **Figure 3**. We here report the complete record of data but also focus on the most recent period (1975–2017; see box in **Figure 3**). The general trend is one of retreat, after two short advance pulses during the Little Ice Age (LIA), culminating in 1822, when the glacier reached its peak LIA extension, and 1861. A very negative phase occurred between 1860 and 1882, when the glacier retreated by 941 m. This phase was followed by a short advance pulse at the end of the nineteenth century. The twentieth century saw an initial stability, with a small advance between 1913 and 1922, after which the glacier underwent an almost uninterrupted retreat, with the only exception of the short advance phase 1973–1985. The cumulative retreat since 1812 was 1.55 km, while since 1913 the glacier retreated by 847 m, with an average of $-7.99\ my^{-1.}$

From 1975 to 2017, Lys Glacier retreated for 32 out of the 43 years analyzed, with an average variation of $-8.26\ my^{-1}$. Since the last short-lived advance phase ending in 1985, retreat totalled 443 m ($-13.85\ my^{-1}$). Retreat rates were particularly high between 2003 and 2007, with the most negative variations of −45 m (2007) and − 38 m (2003), while 1991 saw a very short readvance (+8 m), and in 2002 the glacier was considered stable. Retreat rates became lower after 2007, at $-7.55\ my^{-1}$ preluding to the separation of the glacier tongue from the parent glacier.

4.2 Area and volume changes

Over the period of observation, Lys Glacier underwent large changes in area. From 1975 to 1999, little change is evident on the western section of the glacier tongue (**Figure 4**), which reached the lowest elevations (ca. 2350 m a.s.l.). However, the easternmost part of the glacier tongue had already started retreating by 1999. Far greater changes than in the earlier period occurred from 1999 to 2014, with marked regression both in the western and eastern sections of the glacier tongue (**Figure 4a**). On the western section, the glacier tongue detached from the upper portion of the glacier at the base of an icefall, whereas on the eastern section the retreat exposed steep rocks underneath the ice. In 2014, the two main branches of the glacier still maintained a small connection at the base of a large rock outcrop (**Figure 4a**) and in the accumulation basins. Over the years, changes in Lys Glacier area were almost linear in rate, except for the first year, 1975, when the glacier had its largest area (11.3 km^2) of the period of observation (**Figure 5**). Since 1988, the area decreased at a rate of $-0.045\ km^2y^{-1}$. In view of the high spatial resolution of the imagery, the uncertainty in the glacier outlines is below 2%, which supports the evidence of the general trend.

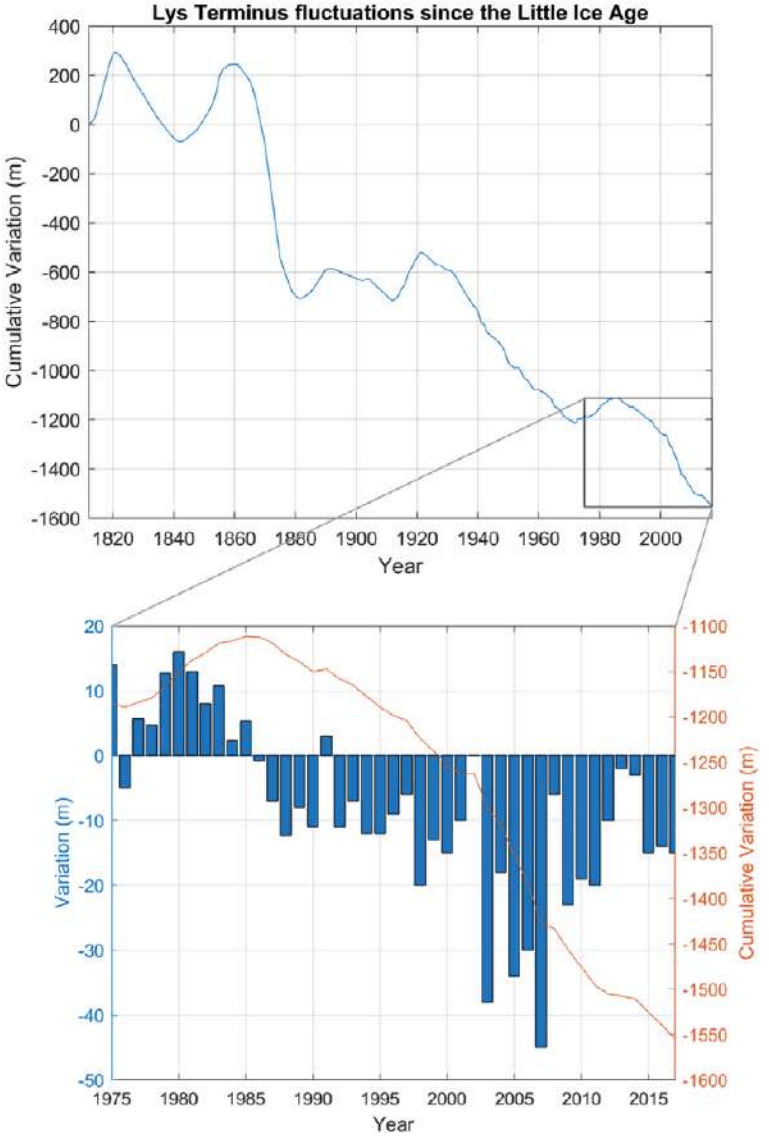

Figure 3.
Lys glacier terminus fluctuations. The box indicates the observation period analyzed in further detail, showing annual variations as well.

Beside changes in the glacier area, recent years have also seen a transformation of the geomorphological setting of the glacier outwash plain. While the exact date marking the origin of glacier lakes is difficult to establish, by 1999 five small ice-contact lakes had formed on the glacier tongue. Progressive stagnation in the ablation area allowed the lakes to grow and new ones to develop. Thus, from five scattered ponds in 1999 (totalling 1527 m^2) a larger overall area is seen together with the coalescence in two larger lakes in 2006 (8730 m^2 in total). In 2014, three further lakes formed while the existing ones grew in size (**Figure 4b, c**). The area of glacier lakes increased almost exponentially (summing the area of all lakes) from 1999, reaching 58,560 m^2 in 2014 (**Figure 5**). The uncertainty in the lake outlines is larger than that of the glacier outlines, up to 30% in 1999 because of their relatively small size.

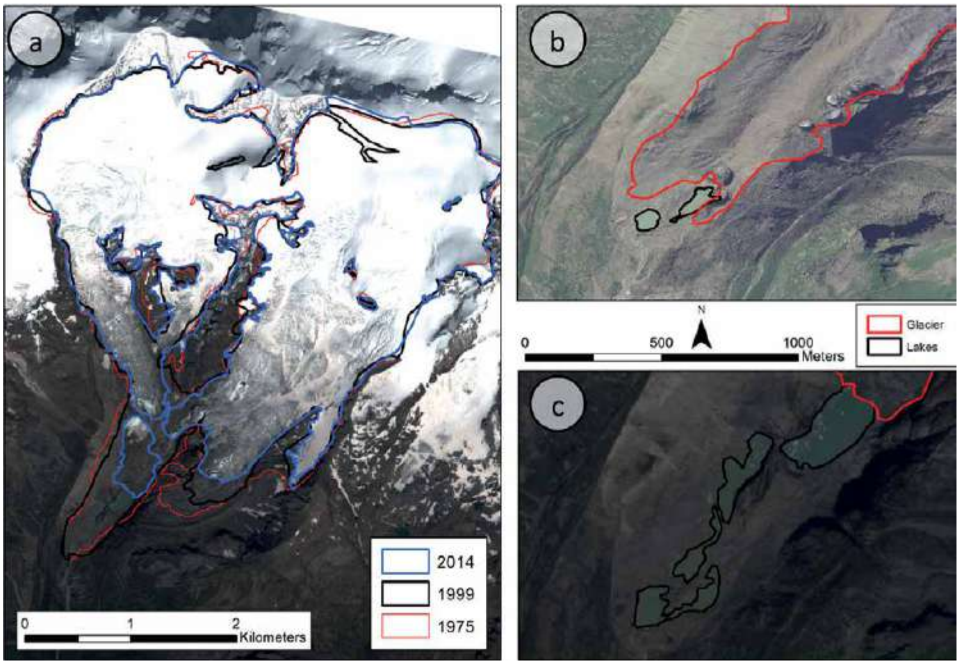

Figure 4.
Area changes of Lys glacier and its proglacial lakes over sample years. (a) Lys glacier outlines in 1975, 1999 and 2014. Background is the orthorectified Pleiades satellite image from 2014. (b) the glacier terminus and two proglacial lakes in 2006. (c) the glacier terminus and proglacial lakes in 2014.

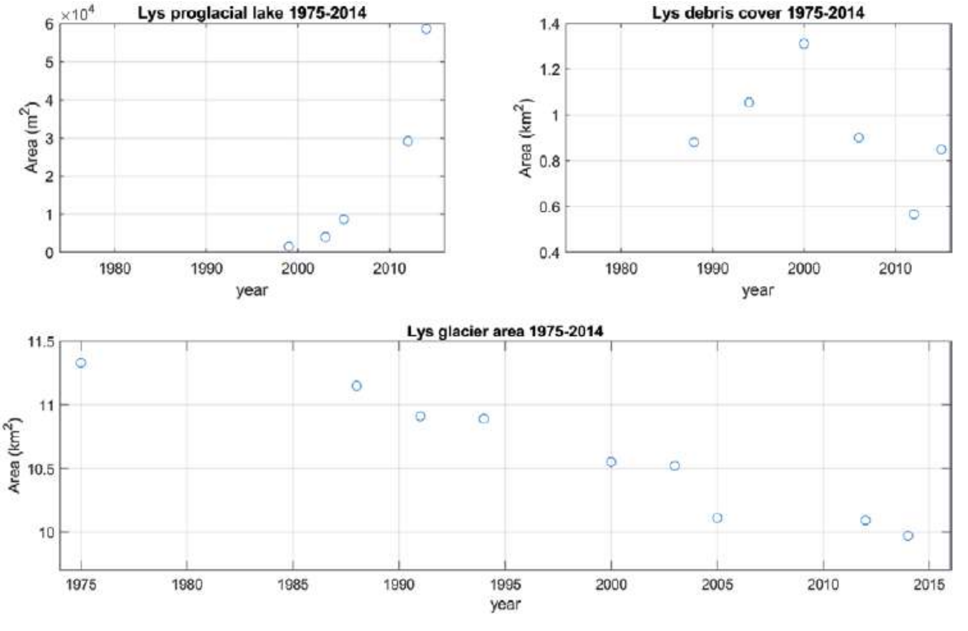

Figure 5.
Changes in the area of Lys glacier, its proglacial lake and supraglacial debris cover over the period of observation.

The DEM comparison shows a very different picture in the glacier tongue compared to the other areas of the glacier. On the tongue, large negative changes occurred, particularly on the western section, with a maximum of 136.52 m ice loss.

On the eastern part of the ablation tongue, the decrease in ice thickness reached instead 41 m. Aside from the glacier tongue, the other areas of the glacier show a more complex pattern, with areas of both positive and negative changes occurring. A loss in glacier thickness is seen particularly in the lower sectors of the western glacier tongue and in a narrow band in the uppermost reaches of the western accumulation basin, as well as on the eastern tongue in its lower easternmost area (**Figure 6**). A positive difference from 1991 to 2014 can instead be seen particularly on the western accumulation basin, where an apparent increase in thickness is

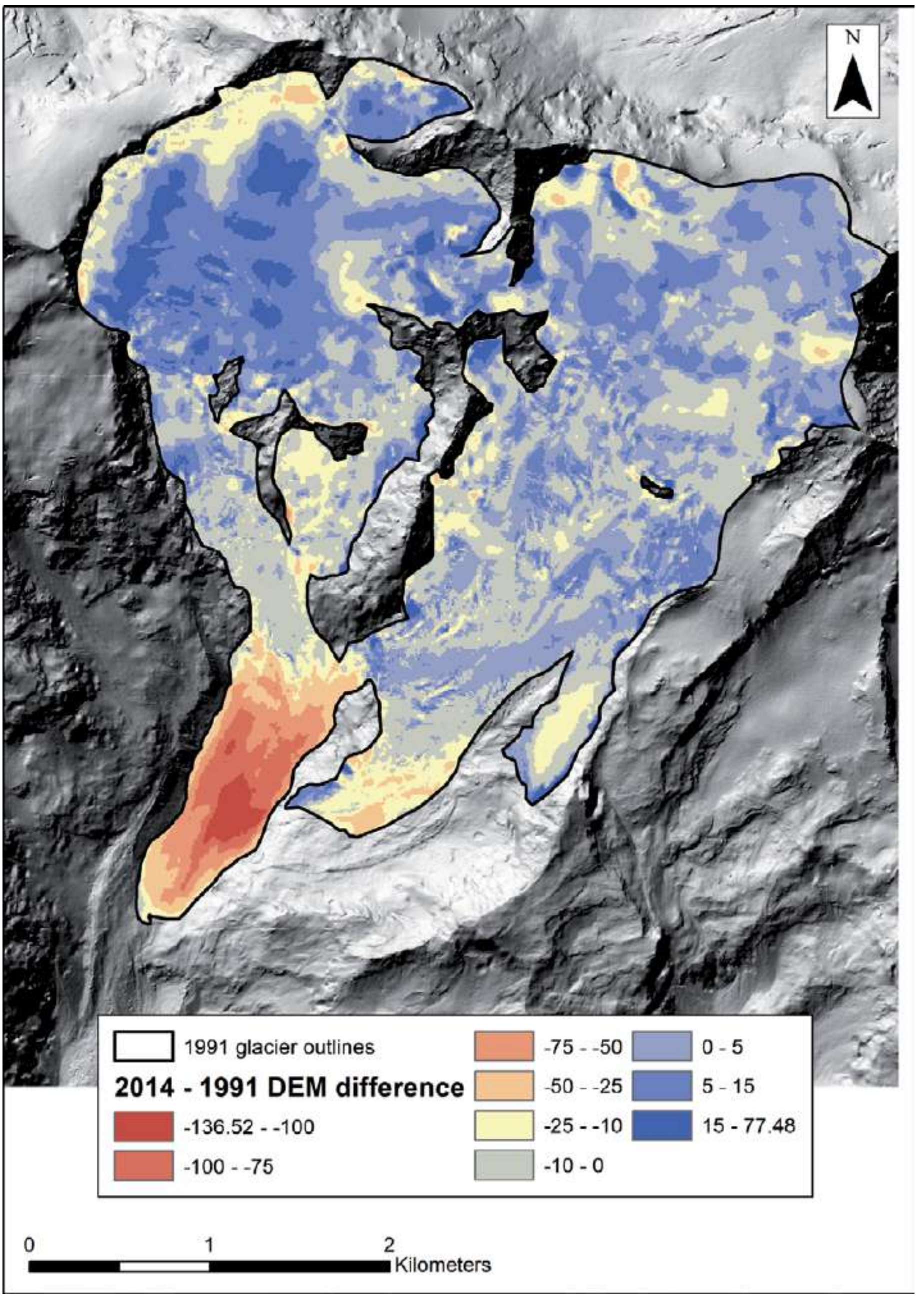

Figure 6.
Thickness changes of Lys glacier from 1991 to 2014. Negative values represent loss in ice thickness. The background image is the hillshade produced from the Pleiades DEM acquired in 2014.

observed between 10 and 20 m, and a maximum of above +75 m was recorded. Considering the entire glacier, the ice loss signal is still predominant, with an average of −4.34 m and a volume change of -47.06×10^6 m^3.

4.3 Debris cover evolution

On Lys Glacier, debris initially increased from 1988 to 2000, when it reached almost 1.3 km^2 on the glacier tongue (**Figures 5** and **7a**). In 1988, debris was present in narrow medial moraines and more abundantly at the terminus (**Figure 2**). In 2000, a more homogeneous coverage of the glacier tongue can be seen (**Figure 7b**), as a mantle of debris appears covering the glacier at the higher elevations at the margins of the western tongue, also suggesting a possible input from the lateral valley walls; conversely, on the eastern tongue and parts of the eastern accumulation basin, coverage is sparse and patchy. Since 2000, the expansion of supraglacial debris appears to have halted as the total area decreased (**Figure 5**): this effect was probably caused by the shrinking of the stagnating glacier tongue, which was however entirely debris-covered by 2005 (**Figure 7c** and **d**). The spread of supraglacial debris appears to have slowed down also at the higher elevations, although limited evidence for increasing coverage is seen for the eastern tongue of the glacier. The relatively high slope and the consequent presence of seracs might limit debris accumulation in those areas.

The accuracy of debris cover maps was evaluated separately for 2006 and 2012, as seen in **Tables 2** and **3**. In both years, PA and UA are very high for debris: both are 100% in 2006, while PA is 89% and UA 97% for 2012. Overall accuracy was 83% in 2006 and 71% in 2012. The limited overall accuracy in both tests is mostly caused by the difficulty in distinguishing between snow and ice (**Figure 7b**, where no ice was identified), which however is not crucial for the analysis of debris cover. We estimate the accuracy of debris cover mapping in other years to lie between the two values reported for 2006 and 2012; however, it is also possible that the debris cover

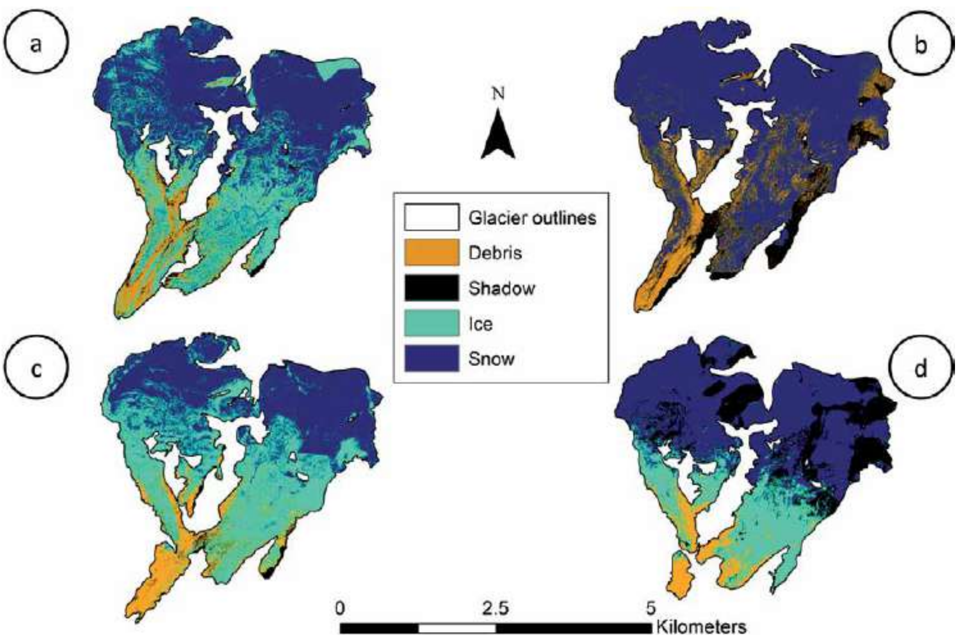

Figure 7.
Evolution of debris cover for Lys glacier. (a) 1988; (b) 2000; (c) 2005; (d) 2014.

		Manually classified				
		Debris	**Ice**	**Snow**	**Shadow**	**Totals**
Predicted	Debris	13	0	0	0	13
	Ice	0	21	17	0	38
	Snow	0	0	48	0	48
	Shadow	0	0	0	1	1
	Totals	13	21	65	1	100

Table 2.
Accuracy estimation for debris cover classification based on the aerial orthophoto from 2006.

		Manually classified				
		Debris	**Ice**	**Snow**	**Shadow**	**Totals**
Predicted	Debris	43	0	0	1	44
	Ice	5	8	23	0	36
	Snow	0	0	20	0	20
	Shadow	0	0	0	0	0
	Totals	48	8	43	1	100

Table 3.
Accuracy estimation for debris cover classification based on the aerial orthophoto from 2012.

amount after 2000 was underestimated, owing to the larger presence of snow cover and shadows in areas which were otherwise classified as debris-covered in previous years (compare **Figure 7b, c** and **d**).

4.4 Climatological analysis

Due to its high altitude and position, Lys valley experiences cold winters and temperate summers. Heavy rainfall can occur when south humid Mediterranean winds blow and collide against the orographic barrier of the southern slopes of Monte Rosa. Perturbations from the west and northwest are more frequent, but they discharge their rain/snow content mainly on the Mont Blanc and Valais areas, leaving the northeastern extremity of the Aosta Valley almost dry.

From 1928 to 2018 (excluding the period 1962–1970 when the station was temporarily moved downvalley), the mean annual temperature at Gressoney d'Ejola station was +4.4°C ranging from +2.6°C in 1984 to +6.1°C in 2015. Since we cannot focus on the commonly used 30-year reference period (1961–1990), we considered 1952–1961 and 1971–1990. Over this period of observation, the mean annual temperature was +4.0°C, slightly lower than the average of the past 30 years (1989–2018), which was +4.6°C. Climate warming is more evident when summer temperatures are compared: from +11.6°C during 1952–1961/1971–1990 to +12.7°C during 1989–2018, with a mean of +12.2°C over the whole period. The hottest month is July with a mean temperature of +13.2°C followed by August (+12.7°C) and June (+10.7°C). Generally, every 3 years the maximum daily of +25°C is recorded, even if the absolute maximum (+28.2°C) was observed on 4 August 2017 and 11 August 2003; 2003 was the hottest summer on record (average + 15.4°C; **Figure 8**) with relatively low amounts of liquid precipitation (216.6 mm corresponding to 74% of the mean summer total, 293.6 mm). Conversely, the coldest summer was 1977 (+9.9°C) with very heavy rainfall (428.6 mm corresponding to 146% of the mean summer total).

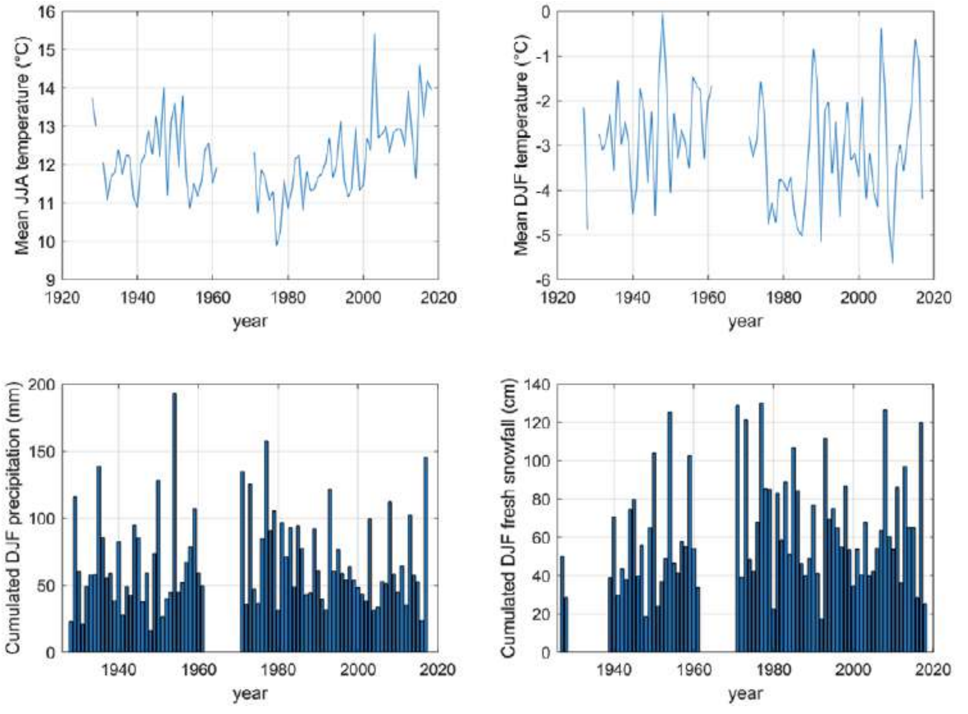

Figure 8.
Climatological analysis of the Gressoney d'Ejola weather station 1928–2018, including mean summer (JJA—June, July, August) temperature, mean winter (DJF—December, January, February) temperature, cumulative winter precipitation (liquid and solid) and cumulative winter fresh snowfall.

During the winter seasons, the monthly mean temperature is −2.6°C in December, −3.6°C in January and – 2.8°C in February with an absolute minimum up to −25.0°C recorded on 10 February 1986. The mean winter temperature is −3.0°C, and the coldest season was 2009–2010 with an average temperature of −5.6°C (and relatively low precipitation: 174.7 mm of total precipitation, 67.5 cm of snow depth, 181 cm of fresh snow; **Figure 8**), while the warmest one was 1948–1949 (0.0°C), also characterized by the lowest total precipitation (48.4 mm corresponding to 24% of the total mean winter amount, 201.4 mm; **Figure 8**), the lowest mean snow depth and cumulative fresh snow (7.7 cm and 52 cm corresponding to 12% of the mean winter amount—63.9 cm—and 28% of the mean winter total fresh snow, 188.7 cm, respectively) and the lowest number of days with snow cover (58 days corresponding to 67% of the mean total winter days, 86.8 days).

Generally, the coldest day is on 5 January (−4.5°C on average). Frost days (T_{max} < 0°C) generally occur from October to April, even if days with T_{min} < 0°C can occur even in July. Thaw (T_{ave} > 0°C) begins at the end of June.

Comparing the two 30-year periods, the mean annual cumulated precipitation (liquid and solid) in 1952–1961/1971–1990 was 1126.9 mm, slightly higher than the amount of 1989–2018 (1090.7 mm). The same results can be observed looking at cumulative fresh snow: from 450.0 cm in 1952–1961/1971–1990 to 385.6 cm in 1989–2018 and from 201.4 cm to 187.5 cm when winter amount are considered. However, the variability remained the same: minima and maxima reached similar values during the two 30-year periods. The maximum total solid precipitation was recorded in winter 1954–1955 (579.7 mm, almost three times the mean value for winter) when very high values of mean snow depth (128.3 cm), cumulative fresh snow (376 cm; **Figure 8**) and number of days with snow cover (90 days) were observed. In this season, the temperature was equal to the average (−3.0°C).

Considering the whole year (average of 1927–2018), 1134.6 mm of rain and melted snow are distributed in 111 rainy and/or snowy days. Total precipitation is lower than the amount falling in the areas downvalley, which are even more exposed to the southerly humid winds, but much higher than the amount received in the dry Aosta Valley where 500 mm per year are generally recorded owing to its intra-alpine position. From November to April, there is an average 371.7 cm of fresh snowfall each year, almost equally divided between the various months: 61.9 cm per month ranging from 54.9 cm in November to 65.9 in December. Heavy snowfalls occur with Mediterranean temperate humid winds, with the daily maximum of 120 cm recorded on 1 January 1986 and the monthly maximum of 250 cm in April 1989.

5. Discussion

Since the LIA, and particularly over recent times, Lys Glacier has undergone remarkable changes in all the investigated parameters of length, area, volume and debris cover. The terminus fluctuation curve for Lys Glacier is strikingly similar to that of other published curves for Mer de Glace (Mont Blanc region, France) and Unterer Grindelwald (Bernese Oberland, Switzerland), which share some of the longest records of terminus fluctuations for alpine glaciers [39, 40], suggesting that in spite of the distance between these glaciers, the climatic setting with a predominant influence from westerly winds is similar. All three glaciers share two distinct advance phases during the LIA, interrupted by a period of retreat, which according to Vincent et al. [41] was caused by a decrease in winter precipitation; small differences however exist in the timing and magnitude of such advances: the maximum length of Lys Glacier in the past two centuries was reached in 1821, similarly to Mer de Glace (and Rosenlauigletscher, [40]), while the extent of Unterer Grindelwald and most other alpine glaciers peaked around the 1850s [40]. Well documented for all three glaciers is also the rapid retreat following the end of the LIA around 1860, although Mer de Glace also shows a small readvance around 1867, for which no evidence exists for Lys Glacier. Both Lys and Mer de Glace then enter a period of relative stability until the 1930s (although marked by several small advances and retreats); a period of marked retreat follows, attributed to enhanced solar radiation [42] lasting until the short-lived advance phase of the late 1960s/early 1970s, which lasted longer, up to 1995, for Mer de Glace compared to Lys and which is generally observed for mostly alpine glaciers [12], although smaller glaciers tend to have larger readvance periods in the twentieth century, indicating a shorter reaction time [43].

At Gressoney d'Ejola, the late 1970s appear particularly favorable years for glacialism, with cool summers and high amounts of winter snowfall. Since the 1980s, a clear warming trend has emerged for summer temperatures, which are 1.3°C higher from the mean of 1971–1989 to the mean of 1990–2017 (**Figure 8**) and 1.1°C higher when including 1952–1961/1971–1989 (+12.7°C in 1990–2017 compared to +11.6°C), while no clear signal can be seen in winter temperatures, total and solid precipitation. This is in line with trends previously observed for Italy [44] and high elevation regions [45] and explains the large retreat rates seen since 1985 (−13.85 my^{-1} in 1985–2017). Considering a longer set of temperature data analyzed for the Alps (1856–1998), the whole twentieth century was characterized by rising temperatures, at a rate of 0.50°C per century (considering summer temperatures [46]), even before the record-breaking decades of the 2000s and 2010s.

As concerns glacier area, the values reported here are always larger than those of the recent Italian glacier inventory (9.58 km^2 in 2005 [14]), even in 2014, because their outlines did not take into account a small area in the eastern part of the glacier, which was here included for consistency with the 1975 and 1991 outlines drawn on the maps. The rate of change of Lys Glacier found in this study (-0.44 kmy^{-1} or $-$ 0.4% y^{-1}) is however comparable to that of alpine glaciers, both in Italy and in the other alpine countries [14, 46, 47]. The increase in debris cover is lower than that reported by Azzoni et al. [9] for the Ortles-Cevedale region, where 38 glaciers were reported to have on average a 13.3% higher proportion of their area covered in debris in 2012 (reaching 30%) than 2003, while Lys Glacier went from 7.9% in 1988 to 12.4% in 2000, decreasing again to 8.5% in 2014. These values are also lower than those reported by Shukla et al. [5] for Samudratapu Glacier in Indian Himalayas, where debris cover nearly doubled over less than 3 years and in line with observations of glaciers in Caucasus by Stokes et al. [11], who describe a 3–6% increase in debris cover and a 57% increase in supraglacial and proglacial lake area. The formation of lakes on stagnating debris-covered glacier tongues was also observed by Kirkbride and Warren [48] and is attributed to the presence of ice-cored moraine which prevents meltwater runoff and favors the accumulation of water in depressions left by melting ice. Similarly to Stokes et al. [11], we also found that debris cover has not halted glacier retreat, counter to the evidence that a thick debris cover is known to reduce ablation (see, e.g. [49]). A field campaign conducted in 2006 revealed that debris thickness is generally above 10 cm and up to 60 cm, well above the critical threshold for which the insulating effect prevails on the albedo effect [49]. Thus, while it is possible that mass wasting would have been even higher without debris, it is more likely that glacier retreat occurred owing to the presence of ice-contact lakes and cavities, which enhance melt through backwasting [50].

Unlike retreat rates, mean thickness and volume changes for Lys Glacier are noticeably lower than in similar studies conducted on alpine glaciers: D'Agata et al. [21] report a decrease in ice thickness of -14.91 m for glaciers in Sondrio Province, Central Italian Alps, from 1981 to 2007, corresponding to -0.57 my^{-1}, while we estimated thinning of Lys Glacier to be 0.19 my^{-1}. In their study of all glaciers in the Swiss Alps, Fischer et al. [37] report an area-weighted mass balance of -0.62 m w.e. y^{-1} from 1980 to 2010, while the geodetic mass balance of Lys Glacier (using a conversion factor of 0.85 accounting for the average density of ice and firn as done by [37]) would be -0.16 m w.e. y^{-1}, which is at the low end of the scale for glaciers analyzed in the study by Fischer et al. [37], although a few Swiss glaciers do share a similar geodetic mass balance. The geodetic mass balance of Lys Glacier would also be lower than that reported by Berthier et al. [51], i.e. -1.05 ± 0.37 m w.e. y^{-1} for glaciers in the Mont Blanc massif using ASTER, SPOT and Pleiades DEMs between 2000 and 2014. If we exclude the possibility that debris cover has slowed down thinning for reasons stated above, the large differences and the apparent low average elevation changes of Lys Glacier can be explained by (1) the relatively large size of the glacier accumulation basins and the presence of seasonal snow on the Pleiades image (**Figure 2a**) and (2) interpolation errors, especially in the oldest cartographic DEM, also seen particularly affecting the accumulation basins of the glacier where little change is expected to occur over the years [38], while we observe areas with apparent thickening of 20 m and up to 75 m. Considering the glacier tongue, the glacier thinning is however evident: to compare our findings against those of Rota et al. [27], we selected an area below 2660 m a.s.l., corresponding to 0.7 km^2. The average ice loss was computed as 62.92 ± 0.81 m from 1991 to 2014, equal to a thinning rate of 2.74 ± 0.03 my^{-1}, and higher than the values reported by Rota et al. [27], i.e. -1.32 my^{-1} between 1925 and 1953 and $-$ 0.42 my^{-1} between 1953 and 1994, suggesting an increase in the glacier tongue thinning rates. Our values for the glacier tongue are also in line with the findings of Mölg and Bolch [52] who reported an average elevation change of -67 ± 5.3 my^{-1} for Zmuttgletscher (Swiss Alps), albeit for a larger area and a longer period, between 1946 and 2005.

6. Conclusion

In this study, we analyzed the evolution of Lys Glacier, one of the largest glaciers in the Italian Alps, by looking at a variety of parameters: terminus fluctuations were studied from historical sources and glaciological bulletins from 1812 to 2017; changes in surface, debris cover and area of supraglacial/proglacial lakes together with volume changes were examined from cartographic and remote sensing datasets from 1975 to 2014. The glacier length variations were found to be similar to those of large glaciers in the Alps such as Mer de Glace and Unterer Grindelwald, indicating a similar climatic setting in spite of the distance of these glaciers; the worst conditions for the glacier development occurred after the end of the Little Ice Age and since 1985 (−443 m from 1985 to 2017) reflecting increasing temperatures as seen from the closest weather station located at Gressoney d'Ejola. Overall, Lys Glacier has retreated by almost 1.6 km since the LIA.

All the other glaciological findings point to a strong glacier reduction, which is interpreted as an evident impact of climate change: the rate of area change was $-0.04\ km^2\ y^{-1}$ since 1988, while glacier volume decreased by $-47 \times 10^6\ m^3$ from 1991 to 2014. The glacier debris cover increased from 1988 to 2000, when it covered 12.4% of the glacier area, and then started decreasing again, as a result of glacier shrinking, while the area of the proglacial lakes grew exponentially over the same period. We consider the changes in area and debris cover as highly reliable in view of our accuracy assessment (max 2% error in the glacier outlines and accuracy between 90% and 100% when mapping debris cover), while the uncertainty in volume variations is larger because of the lower quality of the input DEM from 1991.

In view of the present conditions of the glacier, which prevent reaching the glacier tongue, remote sensing remains as the only viable option to investigate the glacier variations in the future, while the detachment of the glacier tongue has further complicated studying terminus fluctuations. To further our understanding of the glacier past conditions, other historical sources should be considered, including pictorial documents to lengthen the record of glacier terminus position and aerial photography from the past century to provide more accurate estimates of volume changes.

Acknowledgements

We acknowledge the DAR—Department of Regional Autonomies—of the Italian presidency of the Council of Ministers for funding this research.

The photographic comparison of Lys Glacier was performed by Fabiano Ventura in the context of the project 'On the Trail of the Glaciers'— sulletraccedeighiacciai.com.

Pleiades images were obtained from the European Space Agency (project ID 32535). We wish to thank Val d'Aosta region for providing access to the GPS reports and regional technical maps; the meteorological series from Gressoney d'Ejola is available thanks to the efforts and dedication of Umberto and Willy Monterin.

Conflict of interest

The authors declare no conflict of interest.

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Edited by Masaki Kanao, Danilo Godone and Niccolò Dematteis

Glaciers and Polar regions provide important clues to understanding the past and present status of the Earth system, as well as to predict future forms of our planet. In particular, Antarctica, composed of an ice-covered continent in its center and the surrounding Sothern Ocean, has been gradually investigated during the last half century by all kinds of scientific branches; bioscience, physical sciences, geoscience, oceanography, environmental studies, together with technological components. This book covers topics on the recent development of all kinds of scientific research on glaciers and Antarctica, in the context of currently on-going processes in the extreme environment in polar regions.

Published in London, UK

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ISBN 978-1-83962-594-7