Changes in the glacial and periglacial environment of the European Alps and the Central Asian mountains and their socio-economic implications: a comparison

Martin Mergili, Bernhard Müllebner, Chris Kopf & Jean F. Schneider

Abstract

The European Alps as well as the Central Asian high-mountain systems are experiencing substantial environmental changes. These involve glaciers, glacial lakes, permafrost, the entire hydrologic cycle and the ecosystems. The work presented compares recent and projected changes in the two areas and their possible socio-economic impacts, focusing on glaciers, glacial lakes and permafrost. Austria and Tajikistan are taken as examples. The similarities and differences between the two areas are highlighted as a baseline for climate change adaptation strategies and for further research.

Keywords: glaciers, glacial lakes, permafrost, Austria, Tajikistan

1 Introduction

High-mountain areas are particularly sensitive environments and therefore serve as early indicators for climate change processes. Such indicators include snow, glaciers, permafrost, ecosystems and the water cycle (Beniston 2003; Huber et al. 2005). However, environmental changes may express themselves in different ways and at different rates. The comparison of two or more study regions contributes substantially to the understanding of such processes. The present article focuses on a comparison of glacier and permafrost changes in two geomorphologically, climatically and socio-economically contrasting high-mountain areas: the European Alps and the Central Asian mountains, with Austria and Tajikistan as examples.

Worldwide, there is overwhelming evidence for an accelerated retreat of glaciers over the last few decades. Much of this retreat has been attributed to the evident climate warming. However, glacial retreat is not occurring at the same rates and with the same characteristics worldwide (IPCC 2007). Even though glacier fluctuations contribute a great deal to environmental changes in high-mountain areas worldwide, alpine permafrost also plays an important role. Much research on permafrost has been done in the former Soviet Union (Nekrasov & Klimovsky 1978), in Canada (Harris 2005) and in Switzerland (Haeberli 1975; Haeberli & Gruber 2009).

The interest in glacier and permafrost change is of scientific as well as practical interest. The meltwater from glaciers contributes to the water budget of mountain areas and their forelands. Particularly in the valleys of arid mountain areas, it is highly relevant for the livelihood of the people (e.g. irrigation, hydropower generation), whilst its importance diminishes in humid areas and with increasing distance from the glaciers (Hagg & Braun 2005; Kaser & Grosshauser 2010). The fluctuation of glaciers, often in combination with permafrost dynamics, sometimes results in the formation of hazardous glacial lakes producing destructive outburst floods (GLOFs; Richardson & Reynolds 2000; Haeberli et al. 2010). In general, permafrost dynamics are a prominent preparatory factor for the occurrence of mass movements, but this fact has only recently been widely recognized (Haeberli 1992). Intensive and detailed research was carried out at selected sites in the Swiss and Italian Alps (e.g. Monte Rosa) including measurements and modelling of permafrost temperatures and related mass movements (e.g. Noetzli et al. 2007; Kneisel et al. 2007).

2 Study areas and data

Austria and Tajikistan are mountainous countries comparable in order of magnitude of surface area and population. Austria is characterized by a temperate and largely humid climate. Tajikistan, though also temperate on average, experiences a much more continental climate with dry and hot summers and cold winters. Both countries have experienced a positive trend of mean annual air temperature (MAAT) since 1970.

60–65 per cent of Austria is occupied by the Alps, culminating in the Grossglockner at 3,798 m a.s.l. The average elevation of the country is 950 m a.s.l. Tajikistan is embedded in the Central Asian system of mountain ranges, sharing part of the Alai and most of the Pamir. The highest peak of Tajikistan is Pik Ismoili Somoni at 7,495 m a.s.l., the country's average elevation is 2,970 m a.s.l. (Figure 1). Whilst the prospering Austrian economy is dominated by services, the rural population of Tajikistan still depends on agriculture and suffers from dilapidated infrastructures.

In Austria, the first systematic glacier inventory was compiled in 1969 (Patzelt 1980). A second inventory was prepared in the late 1990s (Lambrecht & Kuhn 2007). In addition, length changes of approx. 100 glaciers are compiled in the annual Glacier Reports published by the Austrian Alpine Club. Detailed long-term monitoring has been performed particularly for the Pasterze Glacier and the Hintereisferner (e.g. Kuhn et al. 1999). In contrast to Switzerland (Haeberli 1975), Austrian permafrost research started no earlier than in 1980 (Lieb 1998). Only recently have attempts been made to take the step from local detailed (e.g. geophysical) studies to overview maps, i.e. the entire Austrian Alps (Ebohon 2007). Only indirect evidence

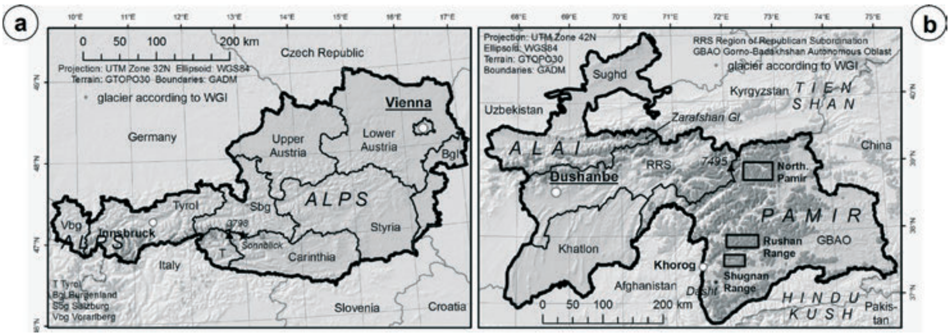

Figure 1: (a) Austria and (b) Tajikistan.

exists for permafrost retreat and related hazards: Krainer (2007) reported problems with increasing rock fall activity and subsidence in permafrost areas.

During the Soviet period, systematic mapping and inventorying of the Tajik glaciers as well as detailed studies took place (Kotlyakov 1980). After independence, research diminished. Direct data on permafrost distribution, properties and impacts in Tajikistan is very scarce. More work exists on the adjacent Tien Shan of Kyrgyzstan and Kazakhstan (Marchenko et al. 2007).

3 Glaciers

The research presented in this paper concentrates on changes and fluctuations in the glacial environment since the late 1960s. Basic geometric data on the glaciers in the two countries (surface area, Equilibrium Line Altitude ELA, elevation of the upper and lower boundary) were extracted from the World Glacier Inventory (WGI) provided by the NSIDC (1999–2009): 7,896 km² of Tajikistan (5.5 per cent of the total area) are covered by glaciers, compared to 542 km² (0.6 per cent) in Austria. The WGI lists 7,126 glaciers for Tajikistan and 925 for Austria, so that the average surface area of single glaciers is 1.1 km² in Tajikistan and 0.6 km² in Austria. The largest glacier in Tajikistan is the Fedchenko Glacier (156 km²), in Austria it is the Pasterze (20 km²). These figures show that the extent of glacierization is about one order of magnitude higher in Tajikistan than in Austria. Due to the climatic and topographic conditions, glaciers occupy a higher altitudinal range in Tajikistan than in Austria. The average ELA, weighted by glacier surface, is 4,896 m in Tajikistan and 2,925 m in Austria (Figure 2a).

Due to widely varying mapping periods, the WGI could only be employed for the general characterization of the glaciers. The glaciers in three selected study areas in the Pamir were systematically mapped from multitemporal satellite imagery: declassified Corona images from 1968 were used as well as ASTER imagery from 2001 to 2009. Rates of glacier surface change vary substantially between different areas in Tajikistan, but also between different observation periods. On average, the observed glaciers in the Northern Pamir remained stable in the period 1968–2002, whilst most glaciers in the Rushan and Shugnan ranges of the Southern Pamir were retreating at rates partly exceeding 1 per cent per year, related to the 1968 surface. In the period 2002–2007, the glaciers of the Northern Pamir were retreating at rates similar to those in the other study areas. Figure 2b shows the changes 1968–2007.

Additionally, the positions of the termini of selected glaciers in the upper Zarafshan Valley (Northern Tajikistan) were measured in cooperation with the Tajik Agency of Hydrometeorology. Including unpublished data on discontinued periodic measurements from the 1920s to 1991 held by the Agency of Hydrometeorology, series of glacier length changes 1927–2009 were derived. The retreat of the glaciers has continued since the 19th century. A steady retreat accelerating towards the end of the 20th century was observed at the Zarafshan Glacier, adding up to approx. 3,900 m from 1927–2009. A similar behaviour was observed for other glaciers in the upper Zarafshan Valley.

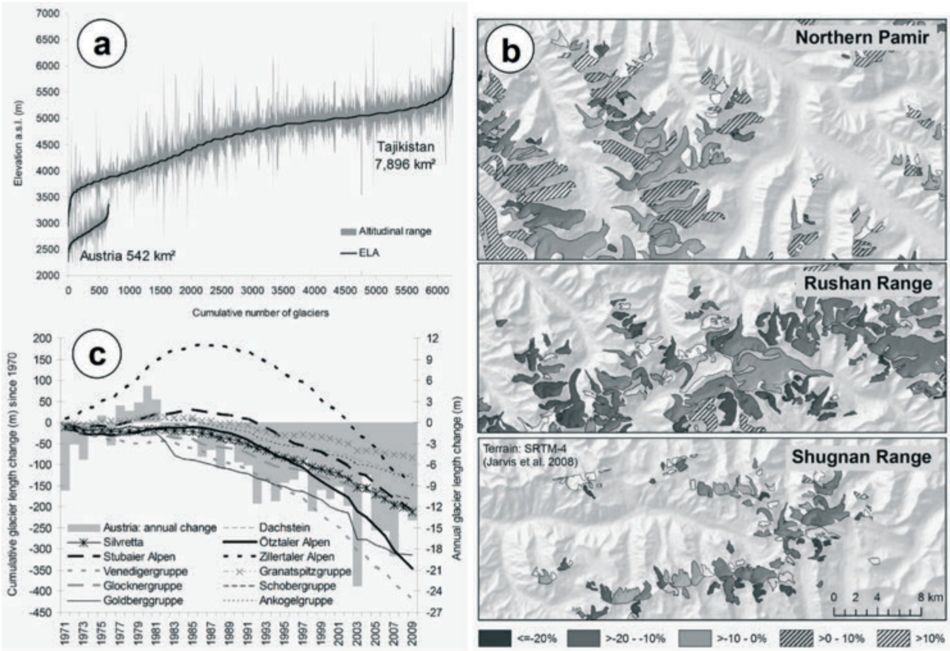

Figure 2: (a) Altitudinal range of equilibrium lines, upper and lower boundaries of glaciers and total glacier surface areas in Tajikistan and Austria, compiled from the WGI. (b) Change of glacier surface in selected areas of the Pamir for the period 1968–2007. (c) Length changes 1970–2009 of selected Austrian glaciers, compiled from the Glacier Reports of the Austrian Alpine Club and averaged by mountain range.

The findings from the comparison of the 1969 and the 1998 Austrian Glacier Inventories presented by Lambrecht & Kuhn (2007) were used to compare the situations in Tajikistan and in Austria: a loss of 17.1 per cent of the glacier surface was reported for the entire country, from 567 km² to 471 km². Whilst the loss in the heavily glacierized Ötztaler Alpen was close to average (17.6 per cent), it was highly variable in the less glacierized mountain ranges. In general, the 1970s and early 1980s were characterized by largely positive mass balances and partial advances, caused by an interplay of years with high winter accumulation and such with low summer temperature (Schöner et al. 2000; Lambrecht & Kuhn 2007). Related to the 1969 surface, the average annual loss until 1998 was 0.58 per cent. This value is comparable to that one found for the Rushan Range (0.56 per cent) and significantly higher than those for the other study areas in Tajikistan for a similar period: 0.40 per cent for the Shugnan Range and 0.01 per cent for the Northern Pamir.

The Austrian Glacier Reports from 1971–2009 (Österreichischer Alpenverein 1972–2010) were compiled and cumulative length changes, averaged by mountain range, were derived. The results are in line with those obtained from the glacier inventories, but they also illustrate the accelerated retreat in the first decade of the 21st century, with the extraordinarily hot summer of 2003 (Figure 2c).

4 Glacial lakes

Retreating glaciers often leave behind a rim of moraines comprised of buried ice overlain by till, an ideal terrain for glacial lakes to form. On the other hand, advancing or surging glaciers can dam lakes in lateral valleys. Some glacial lakes are prone to sudden drainage (Glacial Lake Outburst Floods or GLOFs). GLOFs can evolve in different ways, for example by rock-ice avalanches or calving ice fronts, rising lake levels leading to overflow, progressive incision, mechanical rupture or retrogressive erosion of the dam, hydrostatic failure or degradation of glacier or ice-cored dams. GLOFs often have a highly destructive potential: a large amount of water is released within a short time, with a high capacity to entrain loose debris, possibly leading to a powerful flood with a long travel distance.

For the Southern Pamir, a multitemporal inventory of glacial lakes was prepared from the same set of images as used for the mapping of glaciers. Helicopter surveys and field visits were carried out in summer 2003 and 2009 in order to verify the findings. In 2007, 172 glacial lakes existed in the Gunt and Shakhdara Basins in the Southern Pamir. Most of them are located at 4,400–4,700 m a.s.l. and many have formed – or at least gained much of their size – since 1968. Much fewer glacial lakes exist in other parts of Tajikistan.

The hazard of Glacial Lake Outburst Floods (GLOFs) from the mapped lakes was analyzed using a rating scheme designed for the regional scale (Mergili & Schneider 2011): 6 of the lakes were classified as very hazardous and 34 as hazardous.

History has shown that even small lakes may produce highly destructive GLOFs. On August 7, 2002, one of the numerous glacial lakes in the Southern Pamir drained suddenly. The lake had a surface area of 37,000 m² and an estimated volume of 320,000 m³. The magnitude of the event was multiplied due to entrainment and backwater effects, so that the resulting mud flow had an estimated volume of 1–1.5 Million m³ (Mergili & Schneider 2011). The village of Dasht 10.5 km downstream in the Shakhdara Valley was largely destroyed (Figures 3a and b) and approx. 25 people lost their lives. Field and remote sensing surveys have shown that the lake had formed less than two years before the event, in autumn 2000 or spring 2001 (Figure 3c). The outburst occurred beneath the surface of the natural dam, probably caused by weakening of a temporary blockage of the seepage channel.

Only few glacial lakes exist in the direct forefields of the retreating Austrian glaciers, and none of them are considered hazardous. The main reasons for this phenomenon are probably (1) the much smaller number of glaciers in Austria, and (2) the more limited availability of till. In other parts of the Alps, however, glacial lakes exist and recent hazardous situations are evident (e.g. Werder et al. 2010).

5 Permafrost

Periglacial research presented in the paper focuses on the modelling of potential present and future permafrost distribution. An approach developed by Haeberli (1975) for Switzerland and applied by Ebohon (2007) for Austria was followed, ap-

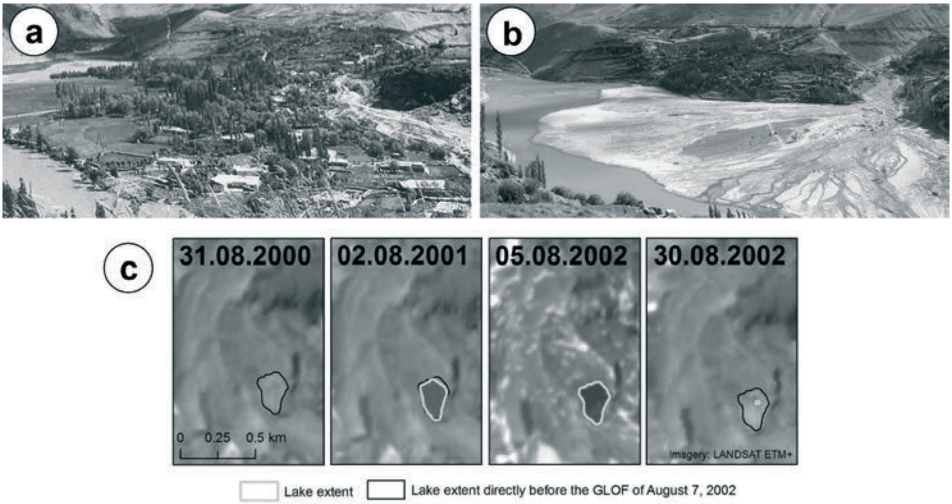

Figure 3: The village of Dasht in the Shakhdara Valley (a) before (photograph: FOCUS Humanitarian Assistance) and (b) after the GLOF of August 7, 2002. (c) The Dasht lake first appeared on Landsat imagery in summer 2001 before draining suddenly on August 7, 2002.

plying lower limits of elevation for the possible and for the probable distribution of permafrost. These limits are based on field evidence and depend on the topographic situation and the aspect. For Tajikistan, the original elevation limits were increased by 1,100 m according to the difference in the 0 °C isotherms. 44.3 per cent of Tajikistan, but only 2.4 per cent of Austria were identified as potential permafrost areas (Figures 4a and b). So were 84.1 per cent of the GBAO (Gorno-Badakhshan Autonomous Oblast) Region. Except for Khatlon, the remaining Tajik provinces also display much larger shares of potential permafrost areas than most of the Austrian provinces. Only the value for Tyrol (11.7 per cent) is comparable to that for the Tajik province of Sughd. More than 90 per cent of the Tajik, but only 63 per cent of the Austrian potential permafrost areas were classified as permafrost probable. In terms of absolute values, almost 54,000 km² of potential permafrost area were identified in the GBAO, out of more than 63,000 km² for the entire territory of Tajikistan. In Austria, potential permafrost areas exceed 1,000 km² only in Tyrol, accounting for almost two thirds of the total for Austria (about 2,000 km²).

The results for Tajikistan were corroborated with 65 rock glacier termini mapped in the Gunt and Shakhdara valleys in the southwestern Pamir. 92 per cent of the rock glaciers are located within designated permafrost areas, but 52 per cent end up more than 200 m above the lower limit of probable permafrost. These findings suggest that the scheme used provides a realistic estimate of the lower boundary of potential permafrost areas, but that rock glaciers alone are of limited use for permafrost delineation.

Scenarios of increasing MAAT (3.7 °C for Tajikistan and 3.5 °C for Austria until 2100; IPCC 2007) were taken as guideline for the projections of the potential future permafrost distribution. Increases in MAAT of 1 °C, 2 °C, 3 °C and 4 °C

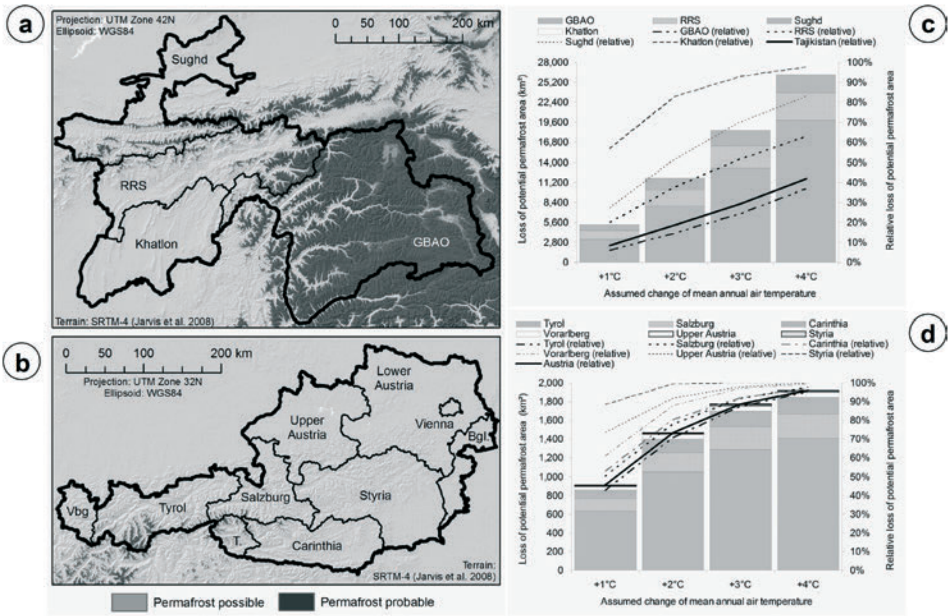

Figure 4: Potential distribution of permafrost in (a) Tajikistan and (b) Austria as well as projected loss of potential permafrost areas in (c) Tajikistan and (d) Austria in absolute and relative terms.

were assumed in order to account for possible scenarios of permafrost retreat in the 21st century. The projected patterns differ markedly between the two countries: in Tajikistan, due to the more extensive potential permafrost area in general, the predicted absolute changes are larger by approx. one order of magnitude than in Austria, whilst the predicted relative changes in Tajikistan are exceeded by those in Austria (Figure 4c and d). In the GBAO, roughly 20,000 km² (40 per cent) would become free of permafrost in the case of a 4 °C temperature increase. The remaining provinces of Tajikistan would experience potential losses of up to a few thousands km², amounting to 63–96 per cent of the potential permafrost areas. These values are comparable to those for Tyrol, the province of Austria with most permafrost in both absolute and relative terms. In each Austrian province, more than 90 per cent of the potential permafrost areas would disappear if the MAAT would increase by 4 °C. In Upper Austria and Styria, with only marginal occurrences at present, there would be no more permafrost at all. Already with an increase of 2 °C, each Austrian province would experience a loss between 70 and 99 per cent. Due to the limited extent of potential permafrost areas in Austria in general, the absolute loss would – except for Tyrol – account for few hundred km² or less.

6 Conclusions and socio-economic implications

The research presented in this paper has illustrated that both in Tajikistan (Central Asia) and in Austria (European Alps), glaciers are in a stage of accelerated retreat. However, more efforts will be necessary in order to make the data from the two countries better comparable.

Indicators also exist for a retreat of permafrost which is, however, more difficult to quantify. The results of simple computer models suggest that much of the permafrost in both countries may disappear until the end of the 21st century. These changes in the high-mountain environment are connected to a changing hazard situation. Interactions of different types of hazardous phenomena involving both the glacial and the periglacial domains may lead to process chains possibly affecting communities tens of kilometres away from the source area.

The extent of the glacial and periglacial environment is about one order of magnitude higher in Tajikistan than in Austria, both in absolute and in relative terms. The decision in which of the countries the changes discussed above pose the more severe problem largely depends on the viewpoint:

- if glaciers and permafrost are considered as environmental features worth of conservation, Austria is much more threatened because much of the glacier surface and most of the permafrost may disappear until the end of the 21st century;
- from a more practical point of view, larger problems are supposed to arise in the mountains of Central Asia. Potentially hazardous glacial lakes are evolving in the front of the retreating glaciers. Huge areas may become free of glaciers and permafrost, increasing the susceptibility of slopes to produce mass movements and, in the latter case, leading to ground subsidence. In Austria, the magnitude of this problem appears comparatively marginal, even though the economic values concentrated at high elevation are higher and damage to infrastructures possibly related to permafrost retreat was reported.

The higher portions of the Western Alps are intermediate between these two categories.

In Central Asia, the population of the valleys strongly depends on meltwater from snow and glaciers for irrigation and therefore livelihood (Kassam 2009). Barnett et al. (2005) highlighted the shift of peak runoff from summer (the time of highest demand) to winter and spring. They mentioned Central Asia as one of the most-affected regions by such a shift. Kaser & Grosshauser (2010), however, showed that the contribution of glacial meltwater quickly decreases with increasing distance from the glacierized areas. Unfortunately, quantitative local and regional data on the real contribution of meltwater from glaciers is sparse. It is clear, however, that the proportion of glacial meltwater in the runoff of Central Asian mountain rivers is much higher than in rivers of the humid Alps (Hagg & Braun 2005). Human-ecological studies of Kassam (2009) have shown that changes in the water – and also temperature – regime are already experienced by the local population in the Pamir, with both positive and negative impacts on their livelihood

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