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A comparison of glacier melt on debris-covered glaciers in the northern and southern Caucasus

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Abstract

The glacier coverage in the Caucasus Mountains underwent considerable changes during the last decades. Besides a reduction in glacier area which in some areas is comparable to area changes in the European Alps, also the concentration of supra-glacial debris increased on many glaciers. Only a few glaciers in the Caucasus are monitored on a regular basis, while for most areas no field measurements are available on a continuous basis. In this study the regional differences between the well studied Adyl-su basin on the northern slope of the Caucasus is compared with a similar basin in the South (Zopkhito basin). Special focus is laid on the effect of supra-glacial debris cover on the melt conditions during the ablation season. Systematic differences can be shown for the distribution and temporal increase of the debris cover on the glaciers. While in the Adyl-su basin an extensive debris cover on the glacier tongues is common, only some low lying glacier tongues in the Zopkhito basin show considerable supra-glacial debris. Also the temporal increase in debris cover is decidedly stronger in the North. Field experiments show that the thermal resistance of the debris cover is somewhat higher than in other glacerised regions in the world. A simple ablation model which includes the effect of the debris cover on ice melt indicates considerably stronger melt rates in the northern basin, despite the much more widespread debris distribution. This is due to the different meteorological conditions with more frequent cloud cover and precipitation in the South. Still ablation is strongly influenced in both basins by the occurrence of supra-glacial debris cover, reducing the total amount of melt on the glacier by about 20%. Especially in the lower tongue areas this effect mitigates the area loss of the glaciers considerably.

1 Introduction

The Caucasus mountain range extends from the Black Sea to the Caspian Sea in a West-East direction with glaciers covering an area of about 1600 km^2 (Stokes et al., 2006). The dominating orientation of the main divide acts as a meteorological boundary between the northern and southern slopes of the mountain range and, in general, larger glaciers are found in the North than in the South. Especially on the southern slopes also climatic changes in West-East direction can be observed, where the western part shows humid conditions, while the East is semi-arid (Volodicheva, 2002). Thus also the water availability for human needs is rather different, depending on the location. As most of the water originates from run-off from the Caucasus range itself, snow and ice melt is crucial for the water production at least in some parts of the region.

In general glaciers are also retreating in the Caucasus. An analysis of Stokes et al. (2006) shows a retreat of glacier area of 10% between 1985 and 2000, whereby more than 90% of the glaciers were affected by retreat.

Especially the summer months of June until August (JJA) are responsible for the main ice melt in the Caucasus (Shagedanova et al., 2009b), as it is the case for many other mountain regions in the northern hemisphere. The JJA mean temperatures are increasing at several weather stations in the Caucasus during the last 40 years, with a rate of 0.05 °C per year (Shagedanova et al., 2009a). The last two decades have been the warmest during almost 80 years of observations, while variations in precipitation do not compensate for enhanced ice melt in this period (Shagedanova et al., 2009b). Therefore glacier melt is expected to increase all over the Caucasus and increased since 2000 (Stokes et al., 2006).

Even though the climatic conditions are rather different across the Main Caucasus Ridge, the glacier reaction between different regions has not been compared in detail. This is also due to the fact that only a few observations are available on comparable glacier conditions. Here we present a study, where the investigations are focused on two regions, North and South of the main divide, where at least some information is available for longer periods.

We focused the field work on the melt conditions of two partly debris-covered glaciers to the North and to the South of the main divide of the Caucasus, namely the Djankuat Glacier (Russia) and the Zopkhito Glacier (Georgia). Apart from the different exposition

(NW and SE, respectively), the mean elevation of the debris-covered glacier tongues is comparable, with the Djankuat Glacier tongue about 100m higher than the tongue of the Zopkhito Glacier. On both glaciers debris covers about 10% of the glacier area and is concentrated on the lower part of the ablation zone. Based on field work in the years 2007 until 2009, sub-debris ablation was analysed in detail. In connection with mass balance investigations on the entire ablation zone and meteorological data, glacier melt was calculated for the respective ablation seasons.

2 Study region and general activities

Ablation underneath supra-glacial debris is very dependent on the local conditions and thus field measurements are required at least on some glaciers which are representative for the studied region. Our test regions for this comparative study are situated in the Greater Caucasus on both sides of the main divide, in a distance of only 64 km from each other.

On the northern side, in the upper Baksan valley, 6 glaciers in the Adyl-su tributary valley have been selected for closer investigation (Fig. 1). Glaciological observations in this area have a long tradition, going back well into the era of the former Soviet Union, with the Djankuat Glacier being one of the benchmark glaciers for the World Glacier Monitoring service (Popovnin, 1999; Haeberli et al., 2009). The total area covered by the glaciers in this valley was 21.4 km^2 in 2003 and the glacier tongues reach down to about 2350 m. The lowest parts of all these glaciers are debris covered.

In the southern Caucasus the glaciers in the Zopkhito Valley, a part of the upper Rioni drainage basin (Fig. 2), were selected for the investigations. Nine glaciers (with a total area of 7.9 km^2, 2006) are situated in this part of the basin. Only two of them, the Zopkhito Glacier and the Laboda Glacier, are partly debris-covered. These two glaciers are the only ones in the region with low reaching tongues (lower limit about 2475 m), where supra-glacial debris can accumulate. The other glaciers are debris-free cirque glaciers at higher elevations.

The field observations on the glaciers were carried out between 2007 and 2009. During the ablation season 2007 detailed investigations took place on the Djankuat Glacier in the northern Caucasus. There ice ablation on the debris-covered parts was the focus of the activities. Two automatic weather stations, installed on the glacier during the same season, provided necessary meteorological data, while temperature gradients in the debris cover were measured with thermistors, in order to derive the thermal properties of the debris cover.

Apart from the short term weather information on the glacier, also longer term meteorological information is required for the understanding of the temporal glacier reaction. Terskol weather station in the main valley of the Baksan river is situated only 20 km from the Djankuat Glacier at 2141 m elevation. Parallel measurements between this station and the automatic weather station at Djankuat Glacier during the summer 2007 (June until October) show a very high correlation for the air temperature (sigma:0.75) and a mean temperature difference of 5.9 °C. Assuming that the observation conditions at Terskol station did not change during the last years, this makes is possible to use a simple lapse rate function, derived from the period of parallel measurements, for calculating the air temperature at the glacier in the past.

During the field seasons in 2008 and 2009 an automatic weather station was also used at the Zophito Glacier. For the southern Caucasus test region parallel measurements are available for the Zopkhito Glacier and Ambrolauri weather station (Fig. 3) which is situated about 45 km (in the direction SSW) from the glacier at 544 m elevation. The correlation between the two stations is good, but smaller as expected. This is probably due to the frequent local rainfall events (accompanied by a drop in temperature) at the glacier during the afternoon in the summer season, while it stays dry (and warm) at the lowland station. The correlation coefficient between the two stations is 0.74 and the mean temperature difference is 11.9 °C.

Based on observations during the field studies, the southern test site shows a decidedly higher cloudiness during summer, due to the advection of humid air from the Black Sea, generating the observed precipitation events. A comparison of air temperatures during the summer 2008 (Fig. 3) shows, however, that air temperatures North and South of the main divide are rather similar on the two glaciers if the vertical temperature gradient is accounted for. Air temperatures at Djankuat Glacier still remain about 0.5 °C lower at comparable altitudes.

3 Analysis of glacier and debris cover evolution

Apart from the actual ablation conditions it is also necessary to evaluate the evolution of the selected glaciers during the recent past, in order to enable conclusions about past and future glacier trends in the region. These glacier change investigations are based on a set of remote sensing images, which are used to delineate the boundaries of the main glaciers within the two basins and their debris cover for different times. By combining the glacier maps with a digital elevation model also the area-elevation distribution and the exposition of the glacier tongues have been determined. Combining all these data makes it possible to characterise the temporal evolution of glacier extent and the debris cover proportion during the last 30–40 years in the selected regions.

For the Djankuat basin information already exists of glacier boundaries and debris extent for six dates from in situ mapping between 1968 and 1999 (Popovnin and Rozova, 2002) and based on remote sensing information in the period 1985 to 2000 (Stokes et al., 2007). In order to update this information a Spot Image from 2006 (spatial resolution 10 m) was used as a reference image for the area delineation. The image was orthorectified using the SRTM 90 m digital elevation model (Jarvis et al., 2008). CORONA imagery dating from 1971 with a spatial resolution of 5 m was coregistered onto the Spot image, but the original spatial resolution was kept to obtain the highest possible accuracy.

In the case of the Zopkhito basin, also a SPOT image from 2007 and Corona imagery from 1971 are the basis of the analysis. Additional information was used for 2006 based on a high resolution Digital Globe image (Google Earth) and for 2008 from Landsat ETM+, in order to obtain cloud free conditions for the entire glacier extent. The glacier boundaries and debris cover were mapped manually on all images, in order to obtain results of similar quality for all of the different image sources.

Glaciers cover an elevation range of 2300 m to 4300 m in the Adyl-su basin and about a fraction of 4% of the drainage area. Between 2900 m and 3700 m the ice cover reaches its maximum extent. The supra-glacial debris cover in the valley is limited to elevations between 2350 m and 3200 m, where the lowermost 150 m show no debris-free glacier surface (Fig. 4). Between 2500 m and 2800 m elevation the areas of debris-covered ice and clean ice show about the same value. Further upward the supra-glacial debris cover gradually reduces to zero close to the first maximum of glacier extent at 3200 m.

In the test region South of the main divide of the Caucasus range, the supra-glacial debris cover is decidedly less expressed. The Zopkhito Glacier shows only a small debris cover on the glacier tongue. Besides supra-glacial moraine ridges across the middle section of the tongue, the debris cover extends mainly over the lowermost part of the glacier. There, continuous and strong melting throughout the summer increases the debris cover on the glacier surface by removing ice and adding intraglacial debris. The debris cover is rather thin on the steeper parts of the tongue, where the material usually is removed by small debris slides leaving only thin dust layers on the ice surface. In the flatter parts, the supra-glacial debris is composed of a wide variety of grain sizes, from very fine grained sand to big stones. Larger boulders however are rather seldom. Figure 5 shows the area-elevation distribution of the Zopkhito and Laboda Glaciers for 2006 (based on elevations from SRTM in 2000). The other glaciers in the basin have no debris cover and are thus not included in this analysis.

The hypsographic curve of the glaciers is similar to that in the Adyl-su basin, but with the lower glacier margin about 100 m higher than in the North. Also the maximum glacier area is situated in a similar elevation band, while the relative area decrease with altitude starts already at about 3400 m, 200 m lower than in the Adyl-su basin. Only the lowermost 300 m in elevation show a significant fraction of debris cover on the glaciers, while small debris covered areas are detected up to 3600 m. In contrast to the

Adyl-su basin, the Zopkhito basin shows considerably larger areas in lower elevation bands. Almost 40% of the total area is downstream of the lowest glacier tongue, while in the Adyl-su basin this is only a small fraction. There the largest elevation bands are concentrated between 3000 m and 3400 m. In the Zopkhito basin, the distribution of these elevation bands stretches between 2100 m and 2800 m.

A comparison of the debris extent on the available remote sensing images shows an increase of the relative debris cover over time (Fig. 6). For the glaciers in the Adyl-su basin, where also imagery is available at intermediate dates, the supra-glacial debris distribution was almost constant at about 16% between 1971 and 1991. After 1991 and until 2006 the debris covered area started to increase noticeably to 23% within 15 years. For the Zopkhito glaciers the increase in debris cover is not so pronounced (from 6.2% to 8.1%) and due to the lack of imagery, no information is available on the temporal pattern of change.

During the same period melt on the glacier tongues exceeded the compensating ice flux which resulted in an area reduction. For the glaciers in the Adyl-su basin this resulted in an area loss of 14.9% for the 25 years between 1971 and 2006. In the Zopkhito basin the resulting area loss is about 12.6% between 1971 and 2006. This reduction is similar to observations in the Alps, where selected regions show a glacier area reduction of 12.2% between 1969 and 2006 (Abermann et al., 2009), but a considerably larger variation of about 18% for the shorter time period 1985–1999 (Paul et al., 2004) which excludes the preceding phase of glacier advances.

4 Measurements and analysis of debris covered ablation

In the Caucasus, as in many other glacier covered regions, debris cover is an important control for ice ablation (Mayer et al., 2010, Hagg et al., 2008). For the detailed observations of recent ablation conditions, a network of 11 stakes was installed in addition to the normal mass balance stake network each on the Djankuat Glacier in June 2007 and in the ablation area of the Zopkhito Glacier in June 2008. The elevation range of the sub-debris ablation network is about 250 m on both glaciers. The stakes were distributed in order to cover representative variations in debris cover, elevation range and exposition.

Installation of the stake networks and subsequent monitoring covered a period from 26/06/2007 until 27/09/2007 at the Djankuat Glacier, while thermistor information of debris temperatures is available until 01/07/2007. At the Zopkhito Glacier the initial stake network was in place at the end of June 2008. This stake network was reinstalled at the beginning of July 2009 and thus could be observed during a second ablation season. The stake height and the thickness of the debris cover were measured after installation in the ice and during subsequent days at all stakes in order to obtain melt rates for different debris thicknesses and meteorological conditions. Both partners, in Russia and Georgia, re-measured all ablation stakes as regularly as possible during the remaining ablation periods. At the Djankuat Glacier the automatic weather station was placed rather close to the location where the temperature gradient in the debris cover was recorded by several thermistors. At the Zopkhito Glacier one automatic meteorological station (AMS) was installed in the upper part of the ablation zone at about 2850 m, just below a steep ice fall in 2008. This station was situated on clean ice. Furthermore, a simpler weather station was installed on a moraine ridge in the central part of the glacier tongue for the duration of the field campaign. This location was also used for the installation of three thermistors in a vertical moraine profile, similar to the setup at the Djankuat Glacier, close to one of the ablation stakes. The full-range weather station was removed in the autumn 2008 and re-installed at a lower elevation on the glacier in spring 2009, ensuring the coverage of meteorological parameters during the following ablation season. In that season thermistors were installed at two locations to obtain additional information about the thermal properties of the debris cover. Ablation was measured frequently at nearby stakes.

In addition also the spatial distribution of the debris cover on the glacier tongue was mapped in detail. This map is used to quantify sub-debris melt rates on a spatially distributed basis and for a later comparison with results from remote sensing imagery.

As an important prerequisite for this analysis the relation between available radiation energy, heat flux through the debris cover and ice ablation needs to be established. Based on measured ablation rates, simultaneous temperature gradient measurements in the debris layer and radiation measurements, the thermal properties of the debris layer can be determined from energy balance considerations and ice melt can be inferred from the solar radiation conditions at the debris surface (Nicholson and Benn, 2006). Ice melt at the stakes was measured frequently during the field campaigns, while afterwards the observations continued on a less dense observation scheme for the rest of the ablation season, as mentioned above.

5 Local characteristics of sub-debris ice melt

In a first step ablation rates and degree day factors in dependence of debris thickness were determined for the ablation season and the results were compared with data from other regions. A relation between the daily mean air temperature and the sub-debris ice melt could be established by assuming the validity of a simple degree day approach (ablation is linearly related to positive air temperatures; Braithwaite, 1981, 1995; Hoinkes, 1955; Hoinkes and Steinacker, 1975).

A critical investigation of the temporal variability of the ablation demonstrates that the established degree day relation is not stable over time. Compared to the first week after installation, melt-rate is generally higher if longer time spans are considered (Fig. 7). The main reason for this observation is probably the considerable mobility of the debris cover over time. After installation of a stake in the drill hole of the debris-covered glacier, the debris cover is reassembled as close to natural conditions as possible. This is, however, only possible to a certain degree and leads to a re-organization of the debris layer over time. At the same time ongoing ice melt will change the ice bed underneath the debris cover and also leads to a re-structuring of the debris cover. Therefore temporal consolidation and probably also removal of fine grained debris material by melt water at some locations leads to a thinning and compaction of the debris cover.

Both processes are linked to higher melt rates due to less insulation and improved heat conduction. In addition, ablation at some stakes shows a rather suspicious behavior. At one location with an initial debris thickness of 12 cm, for example, the degree day factor in 2008 varied from 0.26 to 0.84, a value close to the one for clean ice conditions. This is very probably due to a total loss of the debris cover by water flow or slumping. Such observations demonstrate that ablation measurements need to be carefully analysed, if they are used for quantifying sub-debris melt conditions.

The degree day factors in dependence of debris thickness, derived from quality-checked ablation values, are shown in Fig. 8. Glacier melt is stronger compared to clean ice melt for a very thin debris cover on both Djankuat and Zopkhito Glaciers. The same characteristic has also been observed by other and longer measurements (e.g. Mihalcea et al., 2006; Konovalov, 2000). After this maximum, the melt rate decreases and reaches the same magnitude as for clean ice at the critical debris thickness of about 5–6 cm for both regions. The melt rate continues to decrease rapidly with increasing debris thickness, so that about 50% of the clean ice value is reached at debris thicknesses of about 7 to 8 cm. This thickness for a 50% melt reduction is lower than previously derived values from ablation modelling (Bozhinskiy et al., 1986). However, sub-debris melt varies considerably depending on the local debris layer conditions (grain size, grain size distribution, humidity, etc). Based on our stake observations, however, the strong reduction of ice melt for debris layer thicknesses between 2 cm and 10 cm, compared to thicker debris covers seems well documented for both glaciers.

In order to include the physical properties of the debris layer in the melt calculations, a simple approach is based on conduction as the major process of heat transfer from the surface to the ice. Furthermore, with the assumption of uniform debris conditions over larger areas (similar grain size distribution, similar lithology, similar water content), the heat transfer is governed by the thermal resistance. For daily observations a linear vertical temperature gradient within the debris column can be expected (Nicholson and Benn, 2006) and it can be assumed that the energy transferred through the debris cover depends on the temperature gradient *dT/dz* and the thermal resistance *R* only (Nakawo and Takahashi, 1982):

$$Q_m = \frac{1}{R}\frac{dT}{dz}, \tag{1}$$

where the thermal resistance of the debris cover is defined as the ratio between surface temperature T_s and ablation rate a in dependence of latent heat of fusion L_s and ice density ρ_i, if the mean ice surface temperature is assumed to be at the freezing point

$$R = \frac{T_s}{L_s \cdot \rho_i \cdot a}. \tag{2}$$

At several locations on the glacier temperature gradient measurements in the debris cover were carried out together with the stake ablation readings. From the temperature gradient in the debris cover a mean daily surface temperature can be inferred which is then used together with the recorded ablation values to calculate the thermal resistance. As this is done at locations with different debris thicknesses, a function for the thermal resistance in relation to the thickness of the debris layer can be deduced. One basic assumption for this approach is a characteristic and constant debris composition across the glacier.

A comparison of derived degree day factors in respect to the supraglacial debris thickness for different glacier covered regions shows that the measurements in the Caucasus provide factors in a similar range to the ones determined in the Karakoram (Mihalcea et al., 2006) and the Tian Shan (Hagg et al. 2008). For thin debris layers, however, the variation of the factors is rather large and between the regions the melt rates can vary by a factor three. This is mainly due to geographical conditions (latitude, elevation), the local geology (debris surface albedo, thermal resistance) and meteorological variations (cloudiness). Within the Caucasus there seems to prevail rather similar conditions between the northern and the southern part, as documented by our investigations.

Thermal resistance of the debris cover has been calculated as an independent parameter, in order to allow a comparison between different regions. Ice ablation will be smaller at the Djankuat Glacier in the Caucasus for a given debris surface temperature, compared to the rather similar ablation values at the Baltoro Glacier and the Maliy Aktru Glaciers (Fig. 9). For the Zopkhito Glacier the thermal resistance is smaller than for the Djankuat Glacier and just slightly higher than for the Baltoro and Maliy Aktru Glaciers. Melting is thus enhanced on the Zopkhito Glacier in comparison to its northern counterpart for the same boundary conditions. On the other hand, the degree day factors in dependence of debris thickness for Djankuat and Baltoro glaciers (Fig. 8) are rather similar. This is probably due to the large altitude and thus mean air temperature difference between the two glaciers which, to a certain extent, compensates the physical property differences of the debris cover. The observations also show that within this comparison melt is most effective on the Southern Inylchek Glacier in the Tian Shan. This might be due to regular rainfall in this region, which provides a very effective energy transport by advection in addition to conduction, especially through small debris thicknesses.

6 Model simulations of sub-debris ablation

The temporal development of glacier change and the influence of the debris cover can only be described with a combination of an appropriate mass balance model (including the effect of supra-glacial debris) and an associated model of glacier evolution. One of the key components is the treatment of mass loss from the ablation zone and, in the case of debris covered glaciers, the implementation of the sub-debris melt mechanisms. Field measurements can only be carried out on a finite number of sample glaciers and the step from local field results to calculations for larger areas requires the usage of the above mentioned models.

One major issue when discussing variations in glacier resources is their relevance to the water supply for e.g. hydro power or irrigation. Any hydrological model for run-off simulation in glacierized catchments requires input from ablation models for prognostic calculations into the future. A number of hydrological models already exist which include glacier mass balance routines (e.g. HBV-ETH, or OEZ). There is, however, up to date no adequate treatment of debris-covered glaciers in such models.

In our approach a mean ablation a is calculated for 50 m elevation bands, with an appropriate degree day sum D_s for the individual bands. The total glacier area A and supraglacial debris cover A_d need to be discriminated together with the mean debris thickness h for a correct melt calculation (Mayer et al., 2011):

$$a = \frac{(\mathrm{A}-\mathrm{A}_d)}{\mathrm{A}}\mathrm{D}_s d_f(i) + \frac{\mathrm{A}_d}{\mathrm{A}}\mathrm{D}_s d_d(h) \tag{3}$$

For both cases the simple and widely accepted degree day approach (e.g. Braithwaite, 1995) is used. The degree day factor for ice $d_f(i)$ and the degree day factors function in dependence off different debris thicknesses $d_d(h)$ are calculated from the field data. Also, the distribution of debris thickness with altitude is required for this calculation. A wide range of observations on different glaciers show that in general debris thickness increases with decreasing altitude. For individual glaciers a mean debris thickness function with elevation can be derived and included in the calculations. The summation of the resulting mean ablation rate for the individual elevation bands finally gives the total ablation for the entire ablation zone. The debris cover thickness for the glaciers in the region was extrapolated from the local thickness measurements, assuming similar thickness/elevation distributions on the neighbouring glaciers. The spatial debris cover distribution for all glaciers is based on classification of optical remote sensing images. The debris thickness is then assigned to mapped debris cover according to the corresponding elevation difference from the glacier snout as on the glaciers with measured debris thicknesses. For the glaciers in the Adyl-su basin the thickness measurements on Djankuat Glacier from 2008 could be complemented by detailed debris mapping on this glacier in earlier years (Popovnin and Rozova, 2002). In the Zopkhito basin the measurements of 2008 and 2009 have been the only ground truth source.

In our experiments, the winter snow pack is assumed to be evenly distributed over the ablation area and is melted first using a mean degree day factor for snow (0.54 cm/DD, mean value for similar conditions in Hock, 2003). The amount of snow on the glacier at the end of the winter is derived from precipitation observations and the temperature record, which governs the discrimination between liquid and solid precipitation. As we are only interested in the effect of the debris cover on the ice ablation, mean values for the end of the winter snow pack are used for calculating snow melt and the start of ice ablation.

Based on this melt model the net ablation during one sample year (2008) was calculated for the two regions North and South of the main divide of the Caucasus. The results are shown in Fig. 10. For both regions the calculated equilibrium line altitude (ELA) is in the same range, but lower in the South (about 3100 m in the Zopkhito basin) than in the North (3300 m in the Adyl-su basin). The clean ice ablation, however, shows a larger gradient in the North. This is probably due to the higher cloudiness on the southern slope of the Caucasus main divide which results in smaller values of the surface energy balance for otherwise similar meteorological conditions. This radiation conditions, however, do not lead to a lower general level of the glacier terminus. This effect is probably connected to the mean orientation of the glaciers (northwestward in the North and southeastward/southward/southwestward in the South) and a difference in the precipitation regime with rather large accumulation amounts on the northern slopes of the Caucasus (Popovnin, 1999). Compared to the northern glaciers, the lower limit of the glaciers in the Zopkhito region is about 150 m higher, while the total clean ice ablation at 2450 m elevation is 120 cm or 20% less for the sample year.

In both regions the debris cover strongly influences the total melt. The ablation/elevation function is determined by the debris distribution and the debris thickness. For both examples the effect of the debris cover strongly reduces above about 2850 m due to very little debris cover in the higher reaches. In total, the ice melt is reduced by about 20% due to the debris cover which is almost identical for the two basins. Still the melt characteristics with altitude are rather different, with a more gradual decrease of debris cover in the northern basin.

7 Conclusions

This study compares the conditions of glacier melt on both sides of the main divide of the Caucasus range. In both regions the debris cover plays a moderate role on the melt water production and especially the altitudes below 2800 m are affected by an increasing debris cover in thickness and in areal extent. A clear difference in thermal resistance is probably due to different geological conditions in the basins. This makes the glaciers in the Adyl-su basin somewhat more sensitive to changes in the debris cover. On the other hand, the analysis indicates that the debris cover increases more rapidly in the North than in the South. Due to the climatic and topographic conditions the investigated glaciers south of the divide have almost the same size compared to their northern counterparts, although their exposition is in general more towards the South. The exposition allows higher radiation input and thus more intensive ice melt, which is more than compensated by the general cloud distribution. On the other hand, the higher cloudiness also provides higher precipitation in the South than in the North. Due to the much steeper relief South of the divide the potential areas which could be occupied by glaciers are restricted, so that in general the glaciation is much smaller in the southern slope (Dolgushin and Osipova, 1989). This is also represented in the model results, where for the same time period the effective glacier melt is about 20% less in the South. Still both regions experienced a strong glacier area loss during the last decades and the gradual increase in debris cover only has a moderating effect on the lower 300 m–400 m of the glacier tongues. There the mass loss is reduced by 20–30% which slows down the retreat rates of the glaciers.

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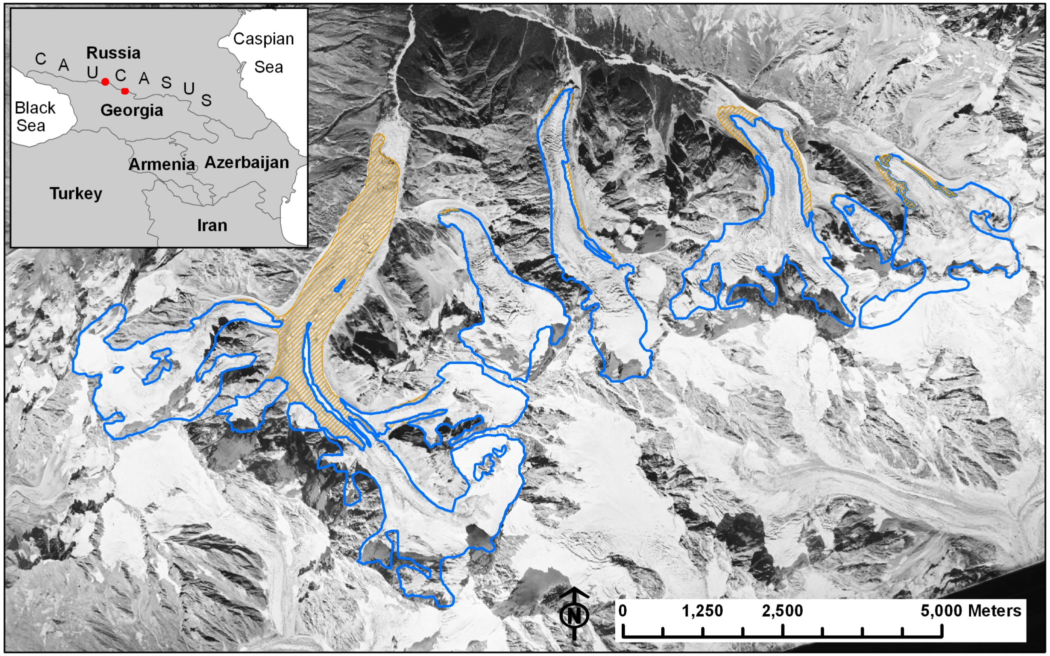

Fig. 1. CORONA image of the Adyl-su Valley from September 1971 with the boundaries of the selected glaciers (the Djankuat Glacier is at the far right) and the supra-glacial debris cover extent (orange).

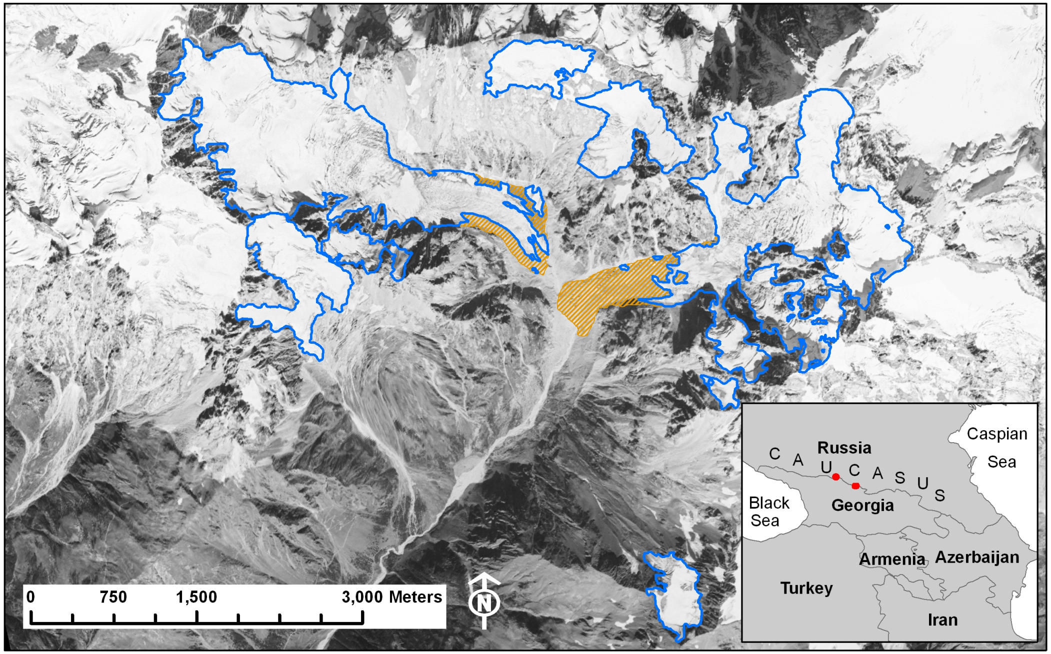

Fig. 2. CORONA image from September 1971 for the Zopkhito basin with the boundaries of all glaciers and the supra-glacial debris cover (orange) of the Zopkhito (right) and Laboda glaciers (left).

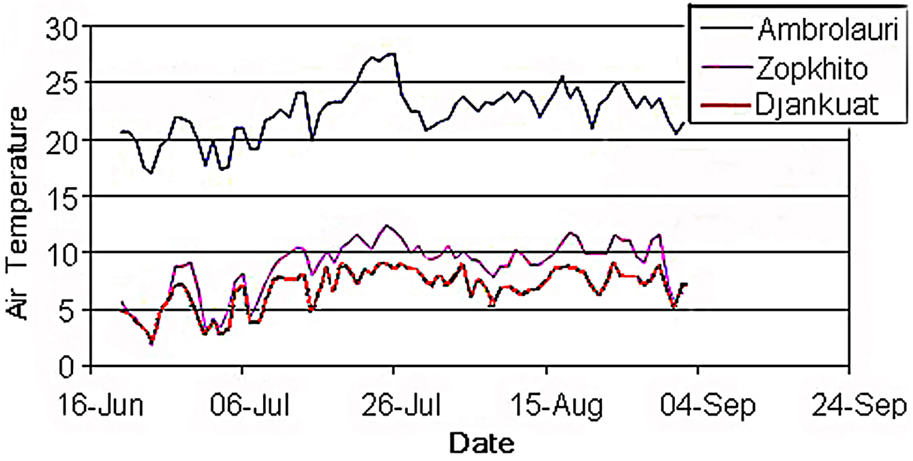

Fig. 3. Comparison of parallel air temperature measurements (°C) on both sides of the Main Caucasus Ridge in 2008: at Ambrolauri weather station (550 m a.s.l.) and on the Zopkhito Glacier (about 2700 m a.s.l.) on the southern slope and on the Djankuat Glacier (2960 m a.s.l.) on the northern slope.

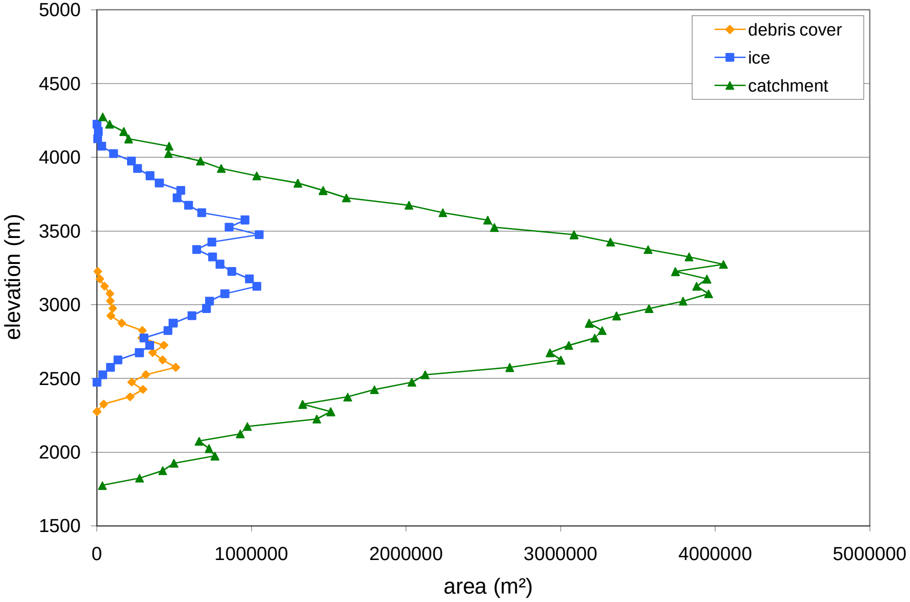

Fig. 4. Area elevation distribution for the six glaciers in the Adyl-su basin in 2000 based on Stokes et al. (2006) and the STRM 90 m digital elevation model. The area distribution is divided into clean ice and debris covered fractions.

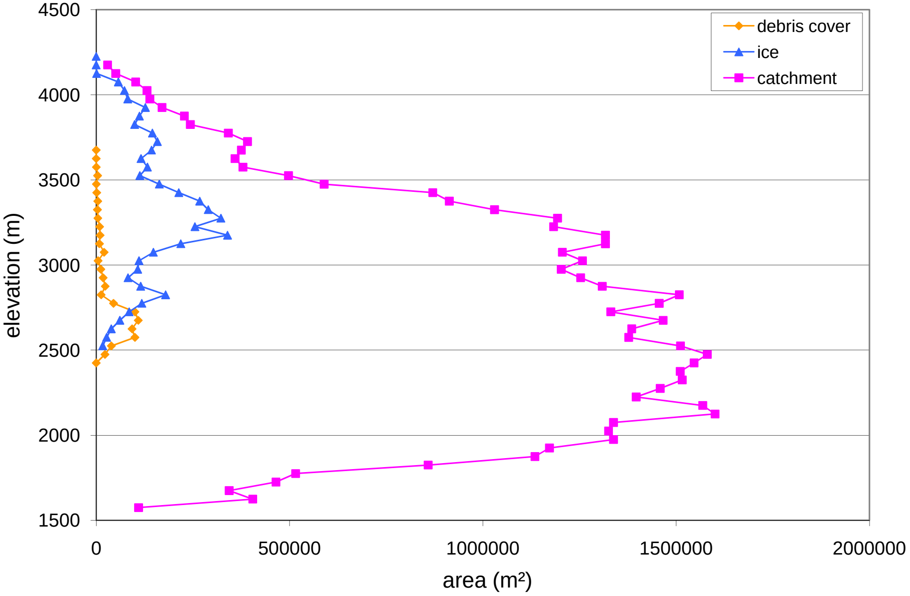

Fig. 5. Area elevation distribution for the Zopkhito and Laboda Glaciers based on the manually delineated glacier boundaries for 2006 and the STRM 90 m digital elevation model.

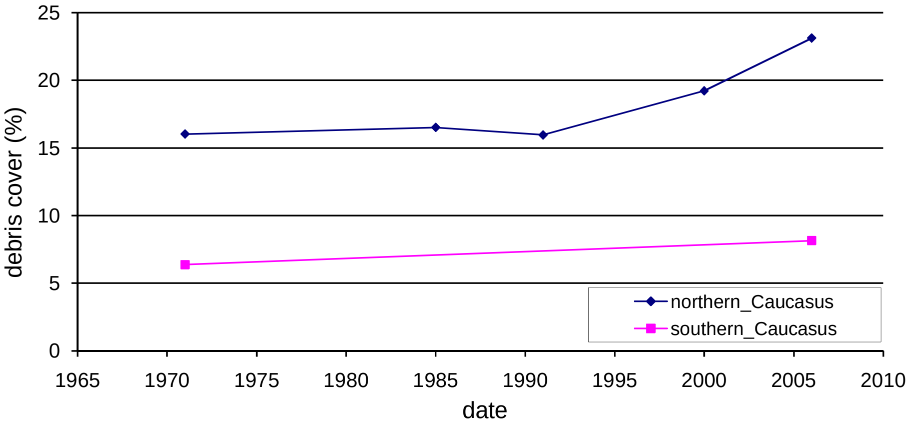

Fig. 6. Relative debris covered area on the glaciers of the two investigated basins in the Caucasus for a time span of 35 years.

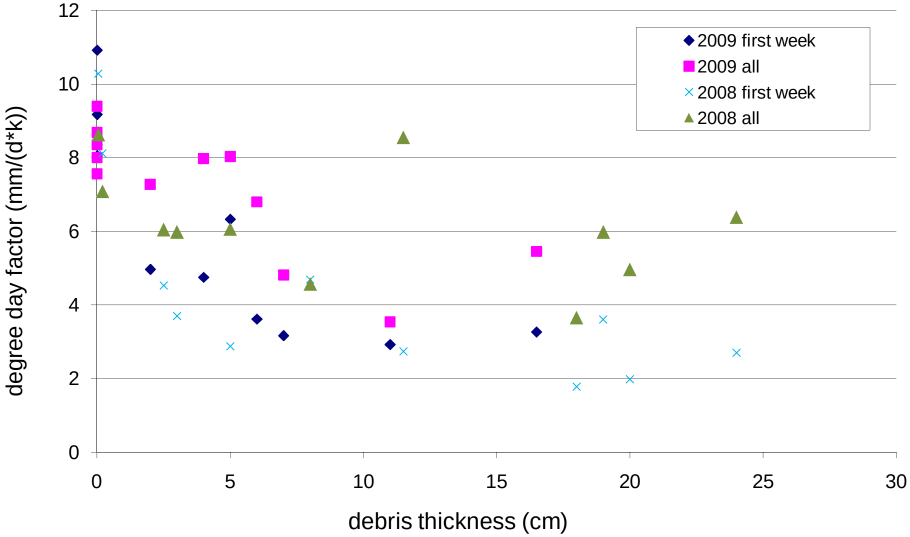

Fig. 7. Degree day factor versus debris thicknesses for all stakes on the Zopkhito Glacier during the observation periods. The maximum ablation is reached for very thin debris layers.

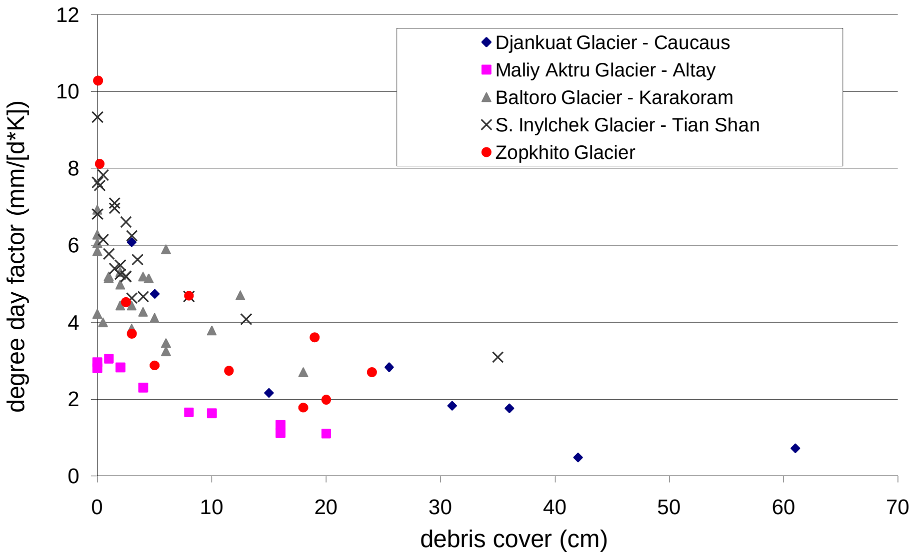

Fig. 8. Degree day factors from different regions (Southern Inylchek, Hagg et al., 2008, Baltoro, Mihalcea et al., 2006, Maliy Aktru, Mayer et al., 2011).

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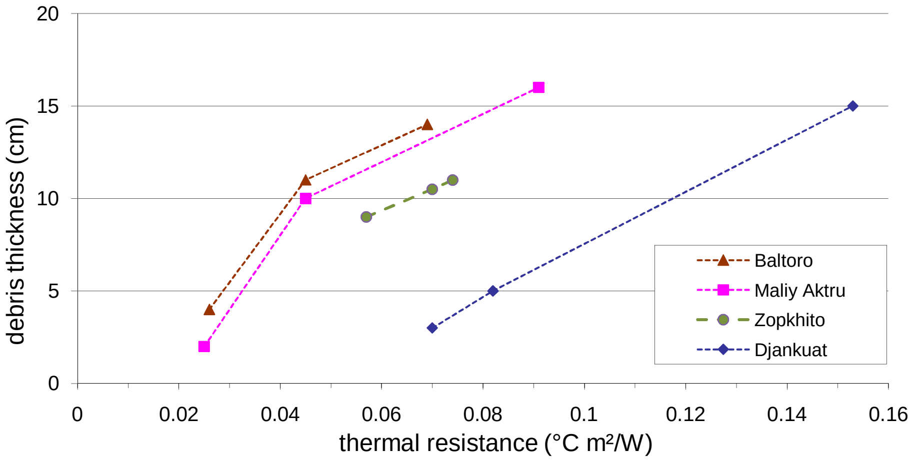

Fig. 9. Thermal resistance for the glaciers in the Caucasus and Altai and compared with results from former field measurements in the Karakoram.

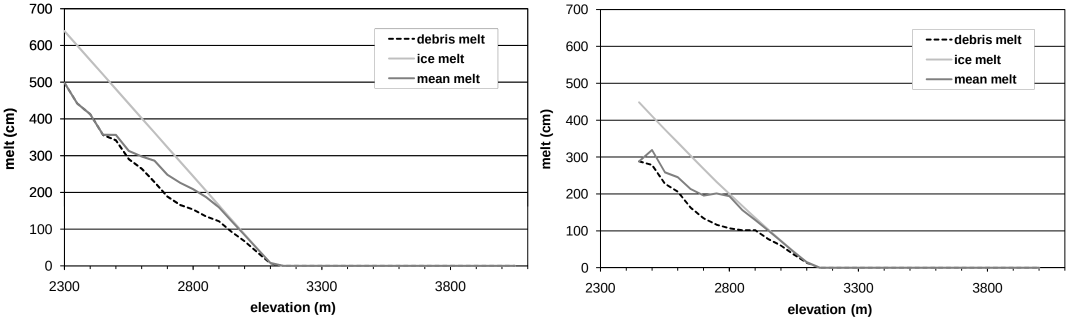

Fig. 10. Model results of net ablation for the two glacier basins and the sample year 2008 (North: left, South; right), based on a degree day approach and including the effect of supraglacial debris. For the sub-debris melt, the specific conditions documented by our field measurements are used for the entire basin. Temperature information is provided by the glacier AWS on the Djankuat Glacier and a weather station at Ambrolauri in Georgia for the Zopkhito basin respectively.