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IMPACT OF CLIMATE CHANGE ON PETROVA GLACIER OF THE AK-SHYJRAK MASSIF (KYRGYZSTAN) USING REMOTE SENSING DATA

ZASTOSOWANIE TELEDETEKCJI DO OSZACOWANIA WPŁYWU ZMIAN KLIMATYCZNYCH NA LODOWIEC PIETROWEJ W MASYWIE AK-SZIJRAK (KIRGISTAN)

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Słowa kluczowe: lodowce, Kirgistan, teledetekcja, Landsat i SRTM

Introduction

Global climate change occurs naturally and periodically and is often attributed to continental drift, variations in the earth's axis and orbit, variations in solar energy output and the frequency of volcanic activity. However, over the past few decades human activities have significantly altered the atmospheric composition, causing a climate change not previously experienced (IPCC, 2001). The first report of the Intergovernmental Panel on Climate Change (IPCC) assessed projections which suggested global average temperature increases between 0.15 and 0.3°C per decade from 1990 to 2005. This can now be compared with observed values of about 0.2°C per decade. It also reported that eleven of the last twelve years (1995–2006) ranked among the 12 warmest years in the instrumental record of global surface temperature since 1850. According to the last IPCC report, the total average temperature increase from 1850–1899 to 2001–2005 was 0.76°C (IPCC, 2007). It is projected that a 1°C rise in temperature would possibly cause alpine glaciers worldwide to shrink by as much as 40% in area and more than 50% in volume as compared to 1850 (IPCC, 2001). The mountain glaciers and snow cover on average have declined in both hemispheres and the maximum areal extent of seasonally frozen ground has decreased about by 7% in the Northern Hemisphere since 1900, with decreases in spring of up to 15% (IPCC, 2007).

Kyrgyzstan is one of the extensively glaciated regions in the world and, according to a catalogue of USSR glaciers, there are 8208 glaciers with a volume 494.7 km^3 which occupies more than 8076.9 km^2 of the territory (Kuzmichenok, 1989). The largest glaciated region in Kyrgyzstan is located in the extreme east, the basin of the Sary-Djaz with 340 glaciers occupied 1581 km^2. There are also relatively larger glacier massifs such as the Alaj ridge, with 1360 glaciers in 957 km^2; the Kyrgyz Ala-Too mountain ridge, with 607 glaciers in 530 km^2; the Northern Kakshaal mountain, with 600 glaciers in an area of 90.8 km^2; the Djangak Basin, with 400 glaciers in an area of 400 km^2; the Talas Ala-Too ridge, with 202 glaciers in 121 km^2; and the southern Kungoj Ala-Too, with 150 glaciers occuping 140 km^2 of glaciated area. The glaciers of Kyrgyzstan are a renewable store of fresh water, with the total amount of preserved water in the mountains in the form of ice and snow estimated at 650 billion m^3. Recent research of Aizen et al. (2007) shows that the glaciers of Kyrgyzstan are also sensitive to climate change: for example the Ak-Shyjrak Range has lost 23% of its area since 1977–2003 and the northern Tien-Shan about 29% from 1955–1990.

Global warming may cause an indirect impact on the landscape, shrinking the mountain glaciers and creating a threat in water supply, irrigation and hydropower production in this region. From a short-term perspective, the discharge may increase due to enhanced melting; but in the long-term discharge might be decreased when the glaciers in a basin become substantially smaller. This could lead to a reduction of water resources and might cause significant changes in the river flow during the dry-season. It should be noted that glacier retreat also leaves unprotected and unconsolidated moraine materials that are prone to landslides, rockfalls, debris flows and enhancemed erosion.

Devastating mudslides occur during the summer time, as a consequence of intense rainfall and glacial melting. As an example of mudflow is the event which took place in the Ala-Archa River (Northern Tien-Shan) on 19 of July 2003, causing several days of anxiety among the citizens of the capital city Bishkek (www.kabar.kg). Over the last few years, mudflows and debris flows on the tributaries of the Ala-Archa River Basin have become more dangerous, because of their frequency. The number of floods, mudflows and debris flows in the Ak-Say River (Central Tien-Shan) basin have increased in the last few years and, as a result of frequent occurrences of mudflows and debris flows from 1960 to 1971 on the cone of the Ak-Say River, there have been human casualties and more than 50 hectares of protected spruce forest were destroyed (KNAF, 1998).

GLOF (Glacial lake outburst floods) are a serious hazard in a mountainous country such as Kyrgyzstan. According to the Ministry of Emergency Situations of Kyrgyzstan, there are 2000 glacial lakes and annually about 200 of them are in a dam-breaking state (Joldubaeva, 2008). One of the largest floods in the Ala-Archa National Park occurred in the Adygene River basin on 2 of June 1953, which was caused by an outburst of a moraine lake in the upper part of the river. On 15 June 1966, the Jashynkul glacier lake, in the Isfairam River basin, burst. A recent GLOF event occurred in the Zyndan River basin in Kyrgyzstan on 24 July 2008, and as a consequence of the flood three people were killed as well as livestock, and heavy damage to lifelines, roads, bridges, houses and pastures were also reported (www.kabar.kg).

A variety of available sources were used in this study in order to detect changes to the Petrova Glacier, which is one of the largest glaciers of the Ak-Shyjrak glacierized Massif in Central Tien-Shan (Kyrgyzstan). Glacier mass change is difficult to measure from the multispectral remote sensing data of Landsat, therefore glacier shrinkage was described as a loss of glacier area. The objective of this study is to characterize changes across a period of more than 60 years, from 1943 to 2006. The total area of glacier in previous years was calculated from the available cartographical data and its recent state from Landsat satellite images. A new policy of free availability of the Landsat data series allows for wider opportunities for monitoring glaciers in remote areas. The extraction of relevant parameters of glaciers from SRTM data also plays a significant role, especially in mountain areas.

Study area

Petrova Glacier (N41ş52'43"– E78ş17'34") is one of the largest glaciers of the Ak-Shyjrak glacierized massif in Central Tien Shan (Kyrgyzstan), with an area of 65.3 km^2 and is located at an elevation between 3730–4948 m a.s.l. (Fig. 1, 3B). The area of the Petrova Glacier was estimated at 75.2 km^2 in 1943 (Kuzmichenok, 1989), 73.1 km^2 in 1977 (based on topographical maps) and 65.3 km^2 in 2003 (Aizen et al., 2007). At the foot of the Petrova Glacier there is a moraine-glacier lake of the same name, which has developed in a basin of intro-moraine depression as a consequence of glacier retreat. According to Jansky et al. (2006) the morphometric characteristics of the Petrova Lake are as follows: area – 3.8 km^2; maximum length – 2.65 km; width – 2.02 km; maximum depth – 69.5 m; and volume – 60.3 mln. m^3. It should be noted that the Petrova Glacier is located about 1.5 km from the Kumtor Gold mining area, which is operated by the Canadian Canterra gold mining and exploration company.

Materials

The 1:50 000 topographical maps of the Petrova Glacier, sheet numbers K44-073-1, K44-073-2 and K44-073-4, from 1977 were scanned at a resolution of 300 dpi and converted into the fomrat required by the software. After georeferencing and the sheets merged, the border of the studied area was delineated and extracted for further analysis.

Many images from the Landsat (WRS-2, Row 31/Path 148) TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus) series collected in June, July, August and September from different years have been acquired. All these data are recorded in the GLCF (Global Land Cover Facility) database. In the pre-processing stage, the analyses have been concentrated on careful selections of the most suitable satellite scenes for the delineation of glacier area change. In order to achieve this goal, only cloud-free scenes were chosen between the end of the melting period, with a minimum amount of snow cover, and the date of snow fall. For this study, only one Landsat TM scene, ID number LT51480312006256IKR00 from 12 of August 2006, was selected. All the Landsat TM bands, except for thermal, have been used in this work,: 0.45–0.52 μm (TM1), 0.52–0.6 μm (TM2), 0.63–0.69 μm (TM3), 0.76–0.9 μm (TM4), 1.55–1.75 μm (TM5) and 2.08–2.35 μm (TM7). Some geomorphologic parameters such as elevation, slope, aspect and topographical index have been extracted from 3 arc second SRTM data (Shuttle Radar Topography Mission).

Meteorological data from the Tien-Shan Station, located at an elevation of 3614 m a.s.l., for the period of 1930–2005 have been analysed in order to determine any change in annual mean temperature and precipitation distribution. These meteorological data were sourced from the Central Asia Database at the University of Idaho.

The analyses were performed using the image processing programs TNTmips (The Map and Image System) version 7.4 (www.microimages.com) and ILWIS 3.3 (www.itc.nl).

Methods

Processing of Landsat TM images includes importing into the software, correcting and extracting he study area. A small correction was needed because of the light scattered back to the satellite sensor by gas molecules and dust in the atmosphere. The path radiance value, or the amount of scattering, is greatest for the blue band and decreases with wavelength, becoming almost negligible for the longer middle-infrared wavelengths band 7. In order to eliminate the path radiance value from each band of Landsat data the Scale/Offset subtraction technique was applied (Jensen, 1996):

$$C = (A + Offset1) * Scale + Offset2 \quad (1)$$

The Normalized Difference Snow Index (NDSI) was used in order to discriminate snow and ice covered areas from snow/ice free areas, by using the formula of Kulkarni et al. (2002):

$$NDSI=Green-SWIR/Green+SWIR \quad (2)$$

In order to discriminate the difference between snow and ice, the Normalized Difference Snow Ice Index (NDSII) was calculated according to the formula (Keshri et al., 2009):

$$NDSII=Green-NIR/Green+NIR \quad (3)$$

For the differentiation of snow free areas, the brightness parameter of the Tasseled Cap transformation (Tasseled Cap Kauth) of the Landsat TM bands was calculated (Getting Started Tutorials, 2007):

$$Brightness_{TM} = 0.33183*TM1 + 0.33121*TM2 + 0.55177*TM3 + 0.42514*TM4 + 0.48087*TM5 + 0.25252*TM7 \quad (4)$$

The Maximum Likelihood classification method of supervised classification was applied and its output validation of is mainly described by the overall accuracy, which is calculated by dividing the total number of correctly classified raster cells by the total number of cells in the training data set.

Results and Discussion

Temperature and precipitation

Annual mean temperature from the period of 1930–2005 for the Tien-Shan Station, which is located at an altitude of 3614 m a.s.l. (N41ş89’ and E78ş13’), is –7.7şC. During the study period the annual maximum of –5.67şC observed in 2002 and the minimum of –9.17şC in 1934. It should be noted that the period from 1997 to 2005 ranked among the warmest years during the period of 1932 to 2005, except for four other warm years 1930, 1931, 1941 and 1980 (Fig. 2). The mean annual temperature for the period of 1997–2005 is –6.3şC, 1.4şC higher than the mean annual temperature for the whole period of 1930–2005. The clear rising trend of air temperature at this altitude for the period of 1997–2003 might have contributed to accelerated melting and might have an impact on glacier size and its mass balance change. Air temperature increase, especially during the summer period in high mountain area, can cause precipitation as rain, rather than as snow. The lack of a new snow layer in combination with the effect o the glacier’s top layer getting dirtier might lower its albedo and accelerate the melting process. For glacial melting as mentioned previously, the summer period with positive temperatures is especially important: therefore the mean temperatures of the summer months for the period of 1930–2005 were calculated for the period of 1930–2005: 2.37şC for June, 4.67şC for July and 4.17şC for August. The mean temperature of the summer months over period of 1997–2005 is 3.4şC for June, 5.3şC for July and 4.8şC for August.

The mean annual precipitation amount is 303 mm for the period of 1930–2005, with a maximum of 512 mm observed in 2000 and a minimum of 96.1 mm in 1997. The data for the Tien-Shan Station shows that 52% of all precipitation falls during the summer period: June, July and August. The winter period is characterized by the lowest amount of precipitation, where the total sum for December, January and February is only 6%. There is no general trend found in the precipitation change as was observed in air temperature fluctuation.

Glacier area change

Pre-processing of the available cartographical data concentrated mainly on correcting, georeferencing, extracting and outlining the border of Petrova Glacier in 1977 from the 1:50 000 scale topographical map and for 1943 and 2003 from the map of Aizen et al. (2007). On the base of these materials the total area of Petrova Glacier was calculated: in 1943 – 75.15 km^2, in 1977 – 73.91 km^2 and in 2003 – 65.33 km^2. According to Jansky et al. (2006), the length of the glacier retreated by 2.67 km from 1869 to 1999 (Table 1). Aizen et al. (2007) reported that the terminus of the glacier gradually retreated for 2.66 km during the period of 1869–2003 (Fig.3A) and the average surface elevation lowered by 19 m from 1943–2003.

In order to define and classify correctly the area of Petrova glacier from the Landsat TM data from 12 August 2006, two NDSI and NDSII indices were calculated. The DN (Digital Number) values of unsigned 8-bit NDSI raster of the study area range from 0–0.93 and NDSII raster values from 0–1. Selection of the appropriate threshold values of snow, ice, IDM (ice-mixed-debris) and debris covered areas on NDSI and NDSII raster is important for its correct delineation. As a slight error may lead to underestimation or overestimation of glacier covered areas, 50 reference points were selected from the topographical maps for further analysis (Fig. 3B). Some geomorphologic characteristics of the reference points were extracted from SRTM data, where elevation ranges from 3765.6–4867.5 m a.s.l., slope from 0–48ş and topographical index from 8.9–24.4.

Table 1. Petrova Glacier length change from 1869–2003

Years	Length (Jansky et al., 2006)		Years	Length (Aizen et al., 2007)	
	Total [m]	Annual [m/y]		Total [m]	Annual [m/y]
1869–1957	1330	15.1	1869–1943	700	9
1957–1980	570	24.8	1943–1956	550	42
1980–1990	380	38.0	1956–1977	400	19
1990–1999	390	43.3	1977–1995	720	40
1990–1999	390	43.3	1995–2003	290	41

On the basis of the brightness parameter, NDSI and NDSII indices the values of the selected 50 reference points were analyzed and thresholds of snow, ice covered areas and snow-free areas were delineated. The lowest values of NDSI are associated with debris and snow-free areas and the highest values with relatively fresh snow. These data were used as a training data set for the Maximum Likelihood algorithm of supervised classification. For this classification procedure, as input data, three bands 7, 5 and 3 of Landsat TM were used. The results of classification and its dendrogram, a tree-like plot, shows the degree of relatedness of the output classes, are represented on Figure 4.

The classification results show that the debris covered area occupies 6.9 km^2 of the territory, Petrova Lake – 3.8 km^2, IMD – 9.4 km^2, ice – 20.7 km^2 and snow – 34.9 km^2. From this information it can be deduced that the total area of Petrova glacier is 65 km^2, which comprises snow, ice and IDM. For the validation of the classification output, a statistical error matrix-based approach was applied and the overall accuracy – 99.47% and Khat statistics value – 99.28% were calculated (Fig. 5).

	Ground Truth Data							
Classific	Name	snow	lake	ice	debris	IMD	Total	Accuracy
	snow	140	0	0	0	0	140	100.00%
	lake	1	52	1	0	0	54	96.30%
	ice	0	0	111	0	0	111	100.00%
	debris	0	0	0	39	0	39	100.00%
	IMD	0	0	0	0	34	34	100.00%
	Total	141	52	112	39	34	378	
	Accuracy	99.29%	100.00%	99.11%	100.00%	100.00%		
Overall Accuracy = 99.47% Khat Statistic = 99.28%								

Figure 5. Statistical error matrix of supervised classification

Conclusion

Meteorological data from the Tien-Shan Station, which is located at an elevation of 3614 m a.s.l. showed that the mean annual temperature for the period of 1997–2005 is higher by 1.4şC than the mean annual temperature for the period of 1930–2005. It can be correlated with the change in the size of Petrova Glacier which has decreased by 10.15 km^2, 7.6% loss of the glacier territory from 1943 to 2006. Evidence for rising temperature is visible in glacier recession and change in the size of Petrova Lake. The area of lake has been changed from 0.2 km^2 in 1911 (Davydov, 1927), 0.8 km^2 in 1947, 0.96 km^2 in 1957 (Bondarev, 1963), 1.83 km^2 in 1977 (topographical map) and to 3.6 km^2 in 2006. According to Jansky et al. (2006) the enlargement of the lake size and volume accompanied by the decrease of moraine stability could cause a very dangerous situation in the case of a dam rupture and an outburst of the lake might wash out the toxic waste storage from the Kumtor Gold Mining and contaminate the whole Naryn Valley, and other parts of country through the Naryn River.

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Streszczenie

Lodowce gór Tien-Szan są odnawialnym źródłem świeżej wody, z której korzystają miliony ludzi w Centralnej Azji. Cofanie się lodowca może być jednym z czynników globalnych zmian klimatycznych. Zgodnie z ostatnim raportem IPCC (2007) całkowity wzrost temperatury od lat 1850–1899 do lat 2001–2005 wyniósł 0.76°C. Oszacowano, że wzrost średniej temperatury o 1°C w stosunku do roku 1850 może spowodować zmniejszenie się powierzchni lodowców górskich aż o 40% i o ponad 50% zmniejszenie ich objętości.

W niniejszej pracy podjęto próbę oszacowania wpływu globalnego ocieplenia na lodowiec Pietrowej, jeden z największych lodowców masywu Ak-Szijrak (Kirgistan), z wykorzystaniem analizy multispektralnych danych satelitarnych oraz dostępnych danych kartograficznych. Celem badania jest scharakteryzowanie rozmieszczenia przestrzennego Lodowca Pietrowej i jego zmian w okresie ponad 60 lat, od 1943 do 2006 roku. Zmiana lodowca bądź masy śniegowej jest trudna do zmierzenia przy użyciu multispektralnych danych satelitarnych Landsat, zatem zmniejszanie się lodowca zostało opisane jako ubytek powierzchni lodowca, który jest funkcją odległości przebytej przez cofający się brzeg lodowca. Do określenia całkowitej powierzchni lodowców zastosowano techniki przetwarzanie multispektralnych obrazów Landsat TM.

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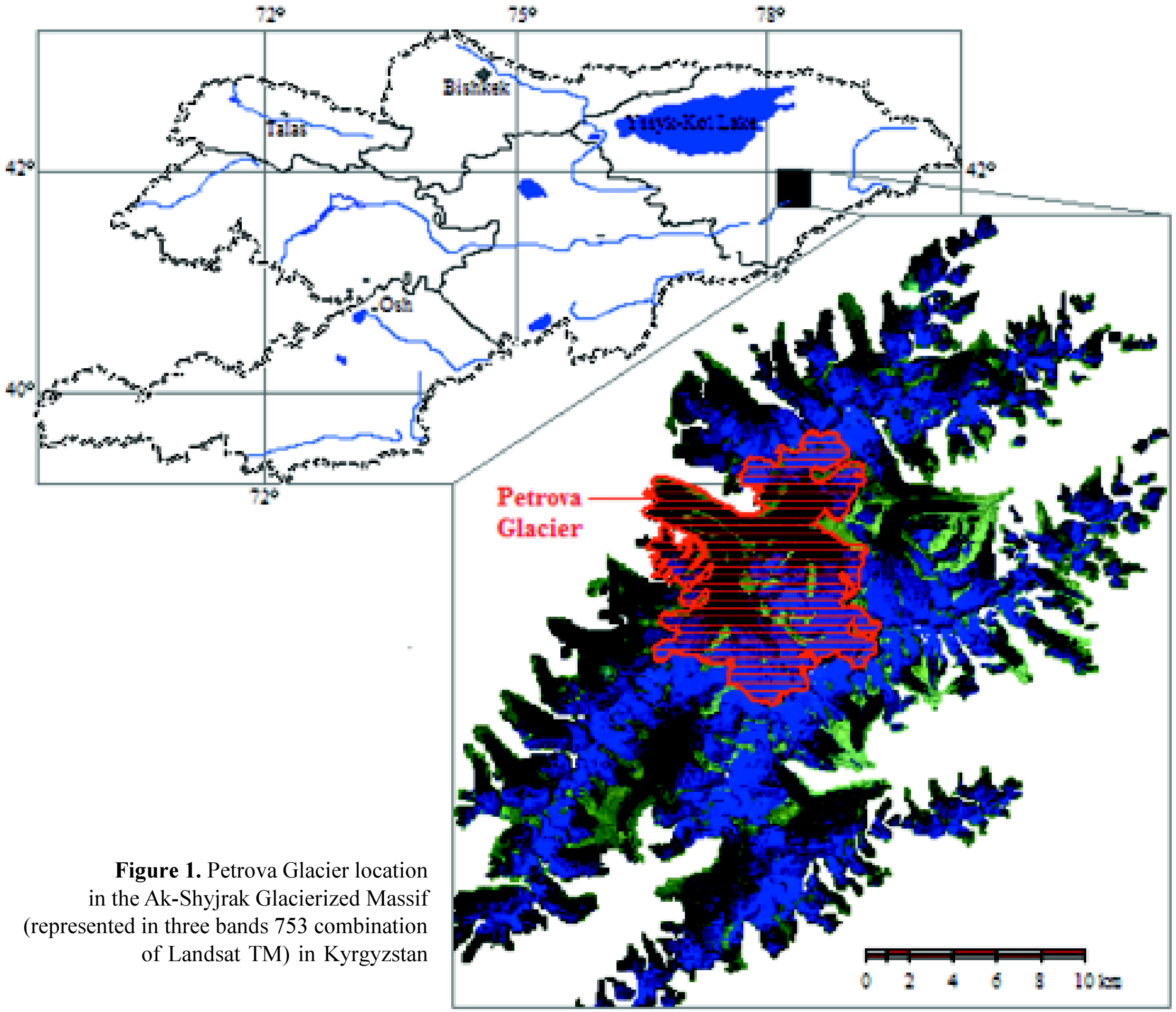

Figure 1. Petrova Glacier location in the Ak-Shyjrak Glacierized Massif (represented in three bands 753 combination of Landsat TM) in Kyrgyzstan

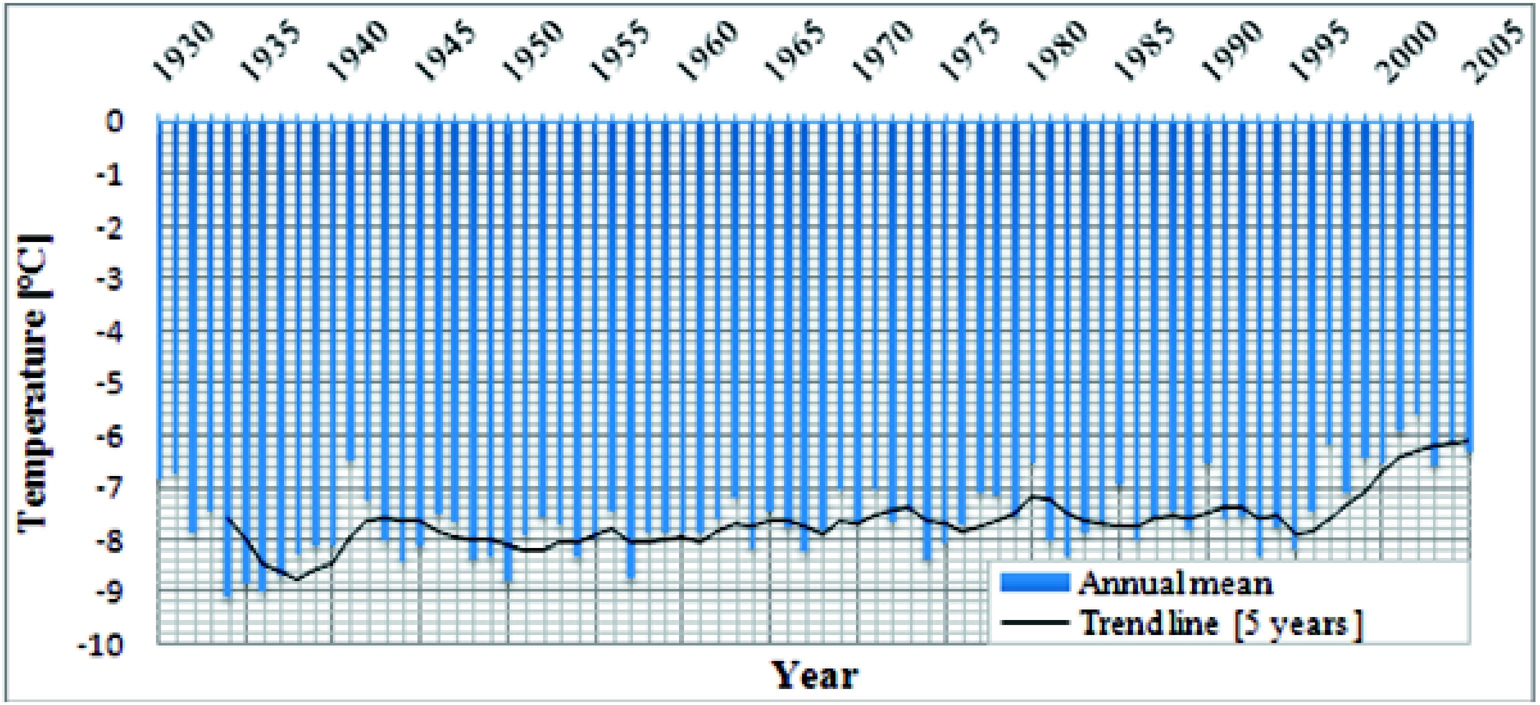

Figure 2. Annual mean temperature for the period of 1930–2005 (Tien-Shan Station, 3614 M a.s.l)

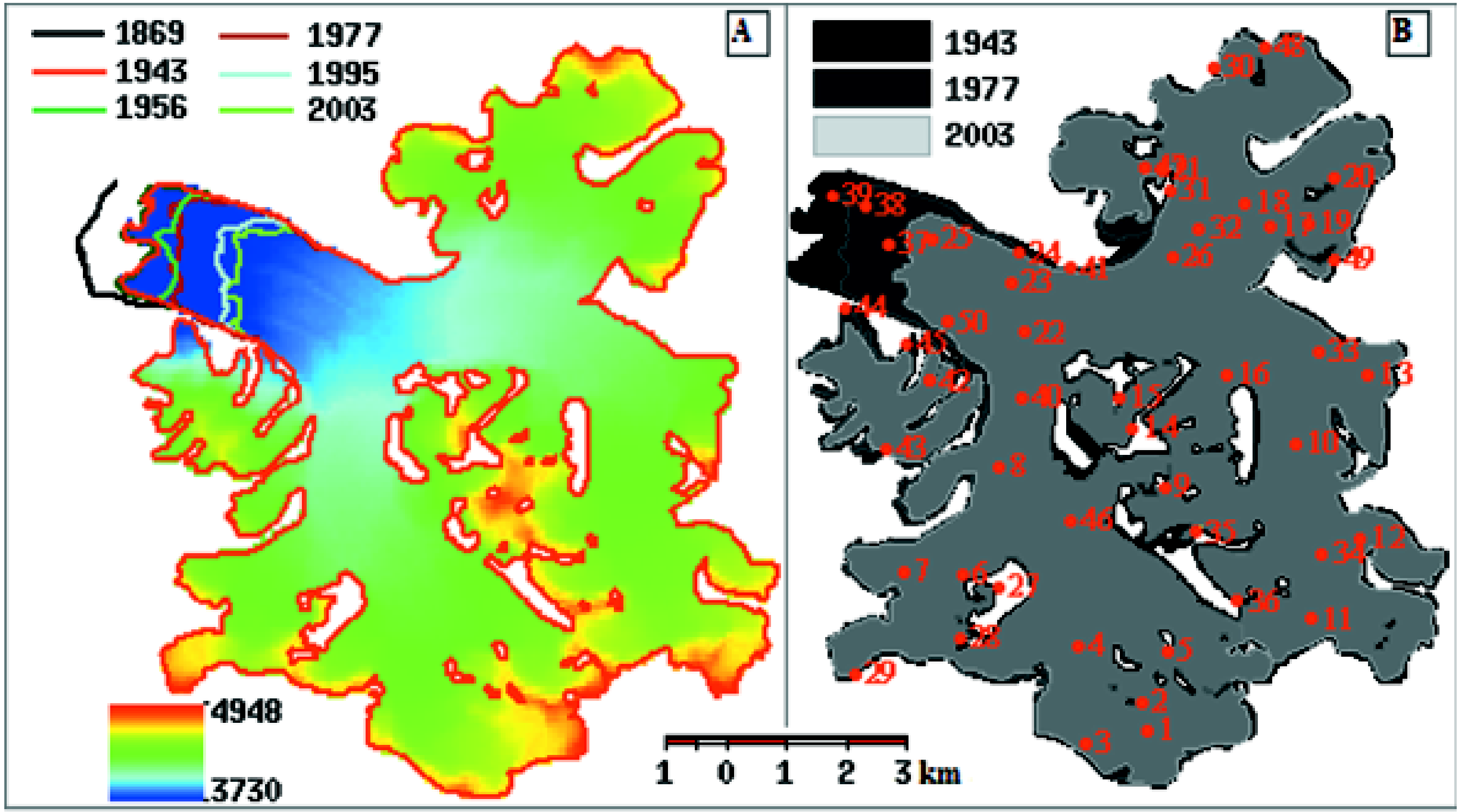

Figure 3. A – Elevation of glacier and its terminus change from 1869–2003; B – Glacier area change in 1943, 1977, 2003 and location of reference points

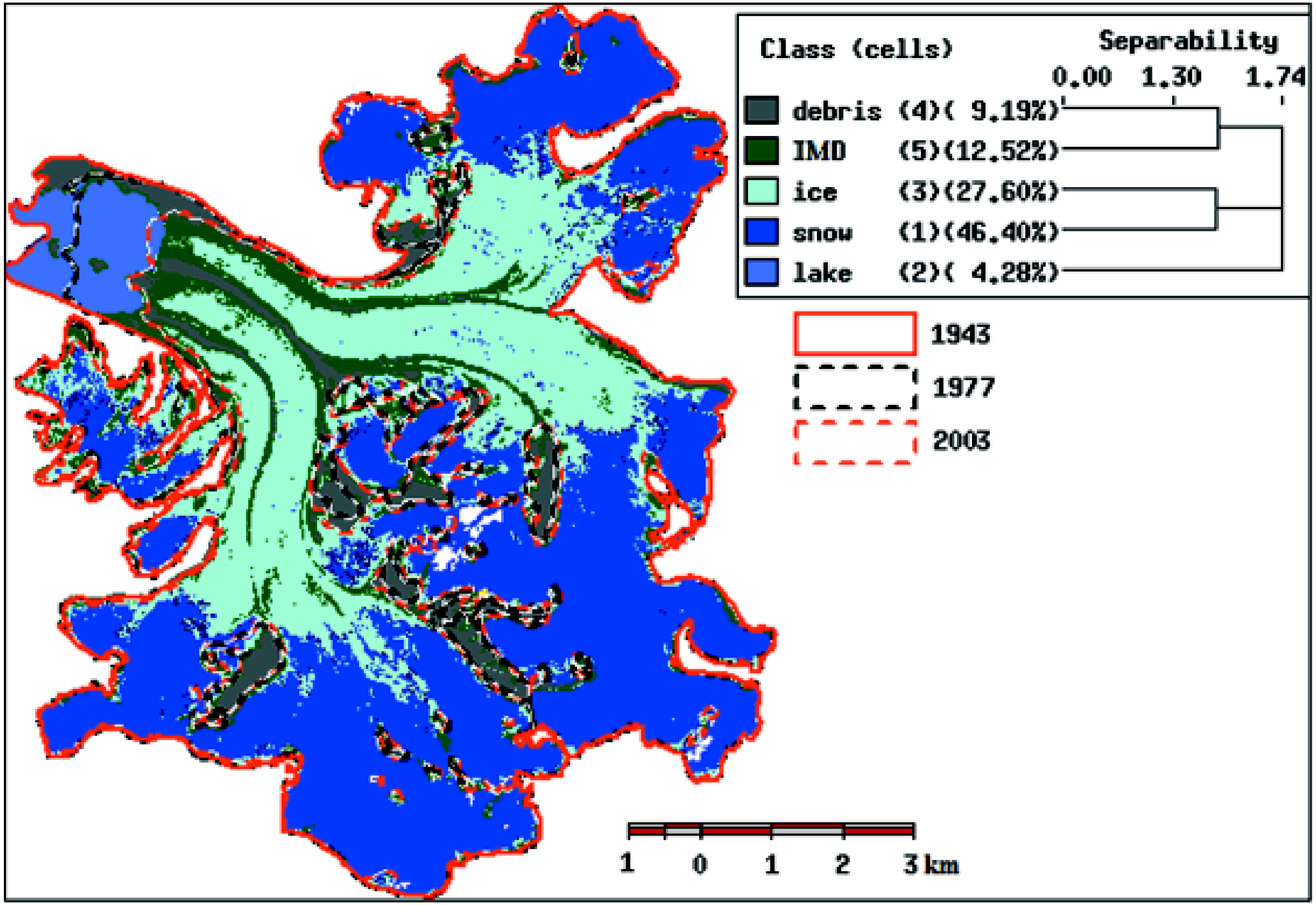

Figure 4. Maximum Likelihood classification results of Petrova Glacier and it's outlined border in 1943, 1977 and 2003