Remote sensing monitoring of the long-term regime of the Pamirs glaciers

VLADIMIR KONOVALOV & LEV DESINOV
Institute of Geography, Russian Academy of Sciences, Moscow, Russia
vladgeo@gmail.com

Abstract Stable shrinkage of the total area of the Pamir glacier is revealed during the entire period of observation. The mean rate of glacier degradation during the period 1980–2000 has increased in comparison with the previous period. Taking into account peculiarities of identification of glacier boundaries on scenes from satellites Landsat 7 ETM+ and TERRA, the characteristics of long-term changes in glacier size should be considered as reliable if obtained by using general assemble or representative sampling.
Key words fluctuation; glaciers; monitoring; Pamir; remote sensing; surges

INTRODUCTION

Total glacier area and its morphological components (accumulation and ablation fields, bare ice and moraine cover) are the main characteristics for hydrological computations and analysing relationships between climate change and fluctuation of glacier size. At present the reference books (Inventory 1971–1978; Schetinnikov, 1997; Osipova *et al.*, 1998) are sources of data on change of glaciers size related to the classes “common” and dynamically unstable or surging (Dolgushin & Osipova, 1982; Patterson, 1984; Osipova & Tsvetkov, 1998). These editions were prepared according to the methodical guides and research (Direction, 1982; Vinogradov *et al.*, 1966). In the first class of objects the main reason for glaciers fluctuation is variability of climate and consequently balance of accumulation and ablation, but in the second class are factors of self evolution of individual glaciers and their interaction with the bed.

LONG-TERM CHANGE IN AREA OF “COMMON” AND SURGING GLACIERS

It was revealed (Schetinnikov, 1997) that the periodical and irregular increments of length of surging glaciers within the Pamir change from hundreds of metres to several (5–7) kilometres on the background of prevailing shrinkage of glaciers during 1966–1980. In this situation it is necessary to estimate the influence of surges of individual glaciers on the validity of the regional relationship between climate and glacier change. A routine photo-survey of high mountain areas from satellite and orbital apparatus is an efficient method for monitoring glacier fluctuation. This work was carried out for the Pamirs glaciers from 1972 to 1999 by means of imagery obtained from the Resurs-F1 satellites and other orbiting platforms such as Salut and Mir. Eighty temporal cuts of monitoring Pamirs glaciers, having a spatial resolution of 5–10 m, were obtained during this time. The results of remotely sensed monitoring of glacier surges are presented in Osipova *et al*. (1998), Atlas (1997), and other publications. After accumulation of the experience of fieldwork and a remote sensing survey, it has become possible to forecast glacier surges (Desinov *et al*., 1978; Dolgushin & Osipova, 1978).

The following data and facilities were used for estimating the state of Pamirs surging glaciers during 1992–2006. (a) Digital photo-survey performed from 2000 on Russian segment of the International Space Station as part of the scientific programme "Uragan", and with a spatial resolution of 5–10 m. (b) Digital multi-channel images of the Earth, obtained from US satellite Landsat 7 (TM and ETM+) in frameworks of international and national projects of monitoring natural resources. Spatial resolution of these images is 28.5–30 m. (c) Digital multi-channel images of the Earth, from TERRA–ASTER imagery within the framework of the GLIMS Project (Raup *et al*, 2007). Spatial resolution of images from TERRA varies between 15 and 90 m and could be analysed using stereoscopic procedures. (d) Application of the known Google Earth facilities for identification and bounding Pamir glaciers. (e) Oblique photography of surging glaciers taken by field expeditions and from aircraft. Identification of surging glaciers and estimation of changes in their state is performed visually and by cartographic analysis of the imagery for different temporal cuts.

Determination of the area of "common" and surging glaciers in the Muksu River basin was performed by means of digitizing glacier contours on images for Pamir obtained from ETM+ observations during September 2000. During the processing procedure, images obtained on Google Earth provided unique and very useful service tools. Spatial distribution of glaciers in the Muksu River basin is illustrated in Fig. 1. GIS IDRISI Kilimanjaro and DEM GTOPO 30, prepared by USGS were used for determination of the area and altitude characteristics of glaciers.

Fig. 1 Location of glaciers within Muksu River basin (Pamir Mountain Region). Data source: Landsat 7 ETM+ image on 2000-08-24.

Some peculiarities of glacier identification by remote sensing survey in 2000, and the influence of the quality of the data obtained and ability to get homogeneous historical range included in past and current estimates of glaciers size, are described below.

(a) The Guide (Vinogradov *et al.*, 1966) recommends using bergschrund and other features for separating seasonal and perennial snow patches on the slopes of river basins from the glacier's nourishment area. In this respect, the date of acquiring remote sensing scenes and snow coverage of the territory are the most important criteria to provide the possibility of correctly digitizing the boundary between the glacier and snow patches outside of its area. It particularly means that by using scenes related to a wet year, we *a priori* overestimate glacier area and this error is unknown.

(b) Existing morphological and dynamical relations of the terminal and backside moraine to the glacier body are considered (Vinogradov *et al.*, 1966) as a condition for including them to the common contour, i.e. glacier + moraine.

(c) No quantitative criteria are applied during the process of visual identification of glacier boundary and thus the final result depends entirely on the qualification of the expert. In addition, there is no option for independent estimation of the quality of work.

(d) The boundaries of morphometric areas of glaciers in the Catalog (Inventory, 1971–1978) were determined by means of processing air-photos at 1:24 000 scale, but during the repeated inventory, space-photo-survey of 1:200 000 scale were used, having less spatial resolution and, consequently, resulting in a not-so-reliable identification of glacier contours if compared with previous estimates.

(e) Ambiguity of recommendations (Vinogradov *et al.*, 1966) on bounding tributaries of dendritic and complicated glaciers made the comparison of changes really difficult, as already noted in Osipova & Tsvetkov (1998).

(f) Spatial resolution of glacier images received after year 2000 from TERRA and Landsat 7 ETM+ is less than remote sensing photo pictures taken in the 1960s or in 1978–1980, thus the recommendations of Vinogradov *et al.* (1966) could not be applied in the same way to keep the previous accuracy. In addition to inventory catalogues for 1971–1978 (Schetinnikov, 1997), original sketches of glaciers are also absent, making the comparative graphical analysis of glacier size for different temporal cuts almost impossible.

Thus there are enough reasons to doubt in unconditional homogeneity the historical range of Pamir's glaciers parameters during 1957–2000 and comparative estimations of state and size of the "common" and surging glaciers within Muksu River basin should be adopted, taking into account the above notes.

ESTIMATION OF GLACIER STATE IN 2000

There were 856 glaciers in the Muksu and Seldara River basins in 1980 (Schetinnikov, 1997). Seldara is in fact part of the Muksu River basin, although we need to consider it separately because inventory data from 1971 to 1978 (Schetinnikov, 1997) listed the main area and altitudinal parameters of glaciers according to 1957 data. It is obvious that to repeat an inventory of 856 glaciers will take a lot of time and labour; therefore data on the change of Muksu glacier size were obtained on a reduced but representative enough sample of the same glaciers in all the considered temporal cuts.

According to the general method for determining composition of representative samples, all glaciers within the Muksu River basin were distributed on their area into two groups. The content of the first group were glaciers with areas greater than 2.0 km^2, and the second group included the rest of the glaciers. The number of objects in 1980 was 206 in the first group and 650 in the second one. The plan was to digitize all glaciers in the first group and to only select from the second group those objects where the altitude of the firn line differs from mean value for the group by no more than ±2%. The total number of glaciers selected in this way was 212. It is known that firn line altitude is a synthetic characteristic for glacier mass balance and condition of runoff formation; therefore it was adopted as criteria for selection of representative samples which present change of glaciers area for the second group. In other words, the following hypothesis was formulated for the second group: mean change of area α_r in representative samples of glaciers for two temporal cuts

$$\alpha_r = \frac{\sum_{i=1}^{n} f_{i(1980)} - \sum_{i=1}^{n} f_{i(2000)}}{n} \quad (1)$$

and in the corresponding total populations α_g

$$\alpha_g = \frac{\sum_{i=1}^{N} f_{i(1980)} - \sum_{i=1}^{N} f_{i(2000)}}{N} \quad (2)$$

are approximately equal. Here $f_{i(1980)}$ and $f_{i(2000)}$ are the area of *i*th glacier in the years 1980 and 2000, respectively, *n* and *N* are number of glaciers in the representative sample and in the total population. In this case it is enough to multiply coefficient α_r on the number of all glaciers with area ≤2.0 km^2. Thus, time and labour expenditure is essentially reduced because it becomes necessary to digitize only 418 glaciers instead of 856. While comparing glacier areas in the years 1957, 1966, 1980 or 2000, they were filtered on area and selected according to the numbers in the Catalog (Inventory, 1971–1978). Analysis of the data on long-term variability of Muksu glaciers, which are presented in Table 1, allowed for the following conclusions: (a) Stable shrinkage of total glaciers area is noted during all long-term observations. Mean rate of glaciers degradation has grown during 1980–2000 if compared with the previous time interval. (b) The process of shrinkage of the total glacier area consists of positive and negative change for areas of individual glaciers. For example, in the Muksu River basin (Seldara excluded) positive change or increase of glaciers area equaled to 85.1 km^2 and negative change or decrease of glaciers area equaled to 104.3 km^2 during the 1966–1980 period, but for 1980–2000 the results were 58.9 km^2 and 135.2 km^2. Similar ambiguity is noted in Tao Che *et al.* (2003) and Severskiy & Tokmagambetov (2005), where the same components of glaciers area changes were described. (c) Because of subjective and objective troubles during recognition of glacier boundaries, the only characteristics of long-term change of glacier size could be considered as reliable if they were obtained by representative data sets.

Surging glaciers of the Pamir are distributed in the Catalog (Osipova *et al.*, 1998) in several groups depending on composition and reliability of identification features of

Table 1 Glaciers area by data (Inventory, 1971-1978, Osipova *et al*, 1998, Schetinnikov, 1997) and satellite remote sensing in 2000. *

Type of data	Muksu River basin						Seldara River basin (Fedchenko glacier)					
	Fgl km^2			dF %			Fgl km^2			dF %		
	1966	1980	2000	1966–1980	1980–2000	1966–2000	1957	1980	2000	1957–1980	1980–2000	1957–2000
All glaciers	1271.9	1239.1	1198.5	2.6	3.3	5.8	732.5	690.2	688.6	5.8	0.2	6.0
682 glaciers	1224.2	1202.3	1128.6	1.8	6.1	7.8	732.4	690.1	688.6	5.8	0.2	6.0
Groups of surging glaciers												
1a	160.2	162.9	154.3	–1.7	5.3	3.7	23.7	23.3	22.4	2.0	3.4	5.4
1b	88.1	75.4	81.6	14.5	–8.3	7.4	53.4	53.4	43.3	0.0	19.0	19.0
2a	215.3	222.3	211.2	–3.2	5.0	1.9	26.7	26.1	28.4	2.2	–8.7	–6.3
2b	56.9	54.9	48.8	3.6	11.0	14.2	52.5	52.0	57.4	1.0	–10.3	–9.3
2c	6.9	3.6	3.1	48.0	13.4	55.0	12.5	9.8	9.8	22.2	–0.6	21.7
2d	62.1	59.6	53.1	3.9	11.0	14.5	0.5	0.3	0.4	36.7	–44.1	8.8
3	152.9	155.3	142.7	–1.6	8.1	6.7	507.0	467.5	473.0	7.8	–1.2	6.7
All groups	742.3	733.9	694.7	1.1	5.3	6.4	676.4	632.4	634.8	6.5	–0.4	6.2
Groups 1a,1b,2a-c	589.5	578.6	552.1	1.8	4.6	6.3	169.4	164.9	161.8	2.7	1.9	4.5
Not classified glaciers												
	481.9	468.4	433.9	2.8	7.4	10.0	56.0	57.7	53.8	–3.1	6.8	3.9

* Fgl, glaciers area; dF, change of area.

the phenomenon. In particular, the probability of surges in the groups 1a, 1b, and 2a–c is considered as unconditional or rather high. These surges were described in Osipova *et al*. (1998). Hence, after obtaining data of change of glacier area in these groups we can estimate the influence of surges on the background fluctuation of glaciers during the time intervals considered in this paper. The results of the above mentioned analysis performed for the Muksu River basin is illustrated in Table 1 and Fig. 2, where negative values correspond to increasing glacier areas and positive to decreasing areas. Comparing the change of glaciers area in the groups 1a, 1b, and 2a–c with data on unclassified objects, we arrived at the following conclusions on peculiarities of glaciers fluctuation at the scale of large river basins:

(a) Surges influence the change of glacier area in groups despite rather long time intervals between estimations. It is confirmed by increasing glaciers area for 1966–1980 in groups 1a, 2a, 2d, and for 1980–2000 in group 2b after comparing them with the group “unclassified glaciers”. Reduction of glaciers shrinkage is noted in Table 1 for components “all groups” and “groups 1a, 1b, and 2a–c” after also comparing them with the group “unclassified glaciers”.

(b) The influence of surges on change of glacier size has local significance and essentially does not affect the background estimate of glaciers evolution at the scale of large river basins within the Pamir Mountain region.

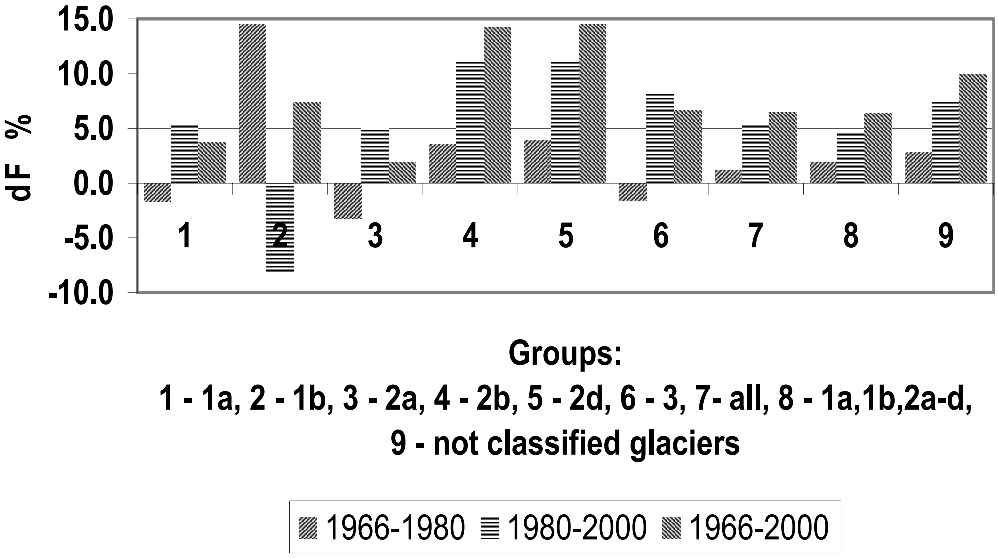

Fig. 2 Change in surface area of the indicated glaciers for two time intervals and the entire period in the Muksu River basin.

CONCLUSIONS

(a) Images of high mountain areas obtained from satellites Landsat 7 ETM+, Terra and others, serve at present as a single source of routine information on regional change of glacier size. Thematic recognition of these images together with simultaneous use of Google Earth imagery provides acceptable accuracy estimations of fluctuations in glaciers if they are based on statistically representative samples. The method of compiling such samples is considered in the paper.

(b) The historical range of data on glacier change included information from both Reference Books (Inventory, 1971–1978; Schetinnikov, 1997; Osipova *et al.*, 1998) and the results of processing satellite images should be considered as conditionally homogeneous. The reason is incompatible spatial resolution of initial materials and the impossibility of using entirely methodical recommendations (Vinogradov *et al.*, 1966) for the interpretation of satellite images.

(c) Observations for short time and speed surges of mountain glaciers are a separate part of remote sensing monitoring of glacier fluctuations within Pamir. Results of this work were grouped according to the type of glacier activity and are presented in Table 2.

(d) Application of remote sensing information enabled the continuous monitoring of surging glaciers within the Pamir region during 1991–2006. The maximal length of advances was observed on the following glaciers: Sugran, Burs, Vali and Maly Saukdara (see Table 2). Surges of those glaciers are very extraordinary natural phenomena, but not yet dangerous to the population and the economics of the Tajikistan Republic.

(e) Locations of previously known surging glaciers at different stage of activity remain the same within the Pamir region during 1992–2005. Period and synchronism of surges is revealed for several glaciers. The state of glacier's surface marked in the Table as BS and A will be used as indicator of their future surge.

Table 2 Characteristics of several dynamically unstable glaciers.

Basin	Glacier name	Number	km L	dL	ΔT, years
Fedchenko Glacier	Vasilevskogo	80	6.5	0.6	1991–2005
Fedchenko Glacier	Kosinenko	9	15.0	0.8	1990–2000
Fedchenko Glacier	MGU	76	6.0	0.8	1991–2005
Vanch	Medvezhiy	118	15.4	0.4	2000–2001
Vanch	RGO	96	23.6	0.5	2002–2004
Muksu		217	5.7	0.2	1979–1993
Muksu	Chakmantash	207	9.8	0.6	?–2002
Muksu		217	5.7	1.3	1991–2005
Muksu		219	3.2	1.6	1973–1980
Muksu	Dzerzhinskogo	265	14.9	2.0	~2000–2002
Muksu	Shini–Bini	776	10.3	2.6	1989–1991
Muksu	Maly Saukdara	274	14.3	2.8	?–2000
Muksu	Vali	257	7.6	3.5	~ 2000–2002
Muksu	Sugran	783	22.0	>5.0	2004–2005
Obihingou	Petra Pervogo	69	12.1	0.4	1988–1991
Obihingou	Burs	307	6.5	2.4	? –2000
Obihingou	Dorofeeva	191	15.1	4.5	1987–1992
Оз. Каракуль	Oktyabrskiy	275	16.7	1.3	1989–1990
Оз. Каракуль	Oktyabrskiy	275		0.4	1990–2002
Kyzylsu	Korzhenevskogo	150	26.2	0–IS	? –2004
Muksu	Bivachnyi	69	29.6	0–IS	1991–2005
Obihingou	Gando	188	22.7	0–IS	1987–1992
Muksu	Fortambek	724	27.2	0–BS	2005
Obihingou	Byrs	772	11.8	0–BS	2005
Vanch	Ravak	171	3.1	0–A	2001–2005
Kyzylsu	Lenina S–W branch	199	12.6	0–A	2004
Obihingou	Shokalskogo	240	25.5	0–A	2005
Obihingou	Vanchdara	264	8.9	0–A	2005
Muksu		219	3.2	–1.1	1991–2005
Obihingou	Sytargi	315	5.1	–0.6	?– 2000
Obihingou		318	5.7	–1.5	? –2000
Obihingou		319	5.8	?	? –2000

L, glaciers length by data of Catalog; dL, change of length; ΔT, duration of process; IS, internal surge; BS, beginning of surge; A, start of activity.

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