

# Changes in Glaciers in the Pskem River basin, Uzbekistan: 1942 – 2020

Semakova, E.\* and Semakov, D.

Ulugh Beg Astronomical Institute of the Uzbekistan Academy of Sciences, Astronomy St. 33, Tashkent, 100052, Uzbekistan, E-mail: ella9sem@gmail.com

\*Corresponding Author

DOI: <https://doi.org/10.52939/ijg.v18i1.2105>



## Abstract

*In response to climate change, most glaciers in Central Asia are losing mass, hence the raised attention due to their impact on the downstream river runoff. This study considers the analysis of glaciers changes in area and elevation in the Pskem River basin, the Western Tien-Shan mountains, using aerial photographs, satellite data of Landsat series, KH-9, and TanDEM-X missions as well as the catalogues data issued since 1960s. Our results revealed a decrease in the glacierized area by 2000 and no significant changes from 2000 to 2020 in the basin. Annual mass balance for 10 investigated glaciers is about -1.08 m w.e. for the period from 2012 to 2014.*

## 1. Introduction

Glacier area and elevation changes, and hence, glacier mass balance is important for understanding glacier ice dynamics and estimating the impacts of their changes on local water supplies and global sea levels (Zemp et al., 2009). The retrieval of region-wide glacier mass balance via space-borne measurement is efficient, safe and cost-effective compared to in situ measurements. Multitemporal optical remote sensing data analysis can be found useful for identifying the glaciers and calculating the change in area while synthetic aperture radar interferometry (InSAR) can work independently of clouds and brightness contrast on ice/snow surfaces and is therefore suitable for obtaining glacier surface elevation. In recent years, the geodetic method for estimating changes in the surface elevation and volume of glaciers has been used not only to estimate decadal mass changes but also to correct and reanalyse long-term glaciological mass balance measurements (Sold et al., 2016). Recent studies of glacier fluctuations in Uzbekistan have focused mostly on areal changes dated by 2007-2011 (Kudyshkin et al., 2014 and Semakova et al., 2016). Elevation changes have been considered for 7 glaciers using two TanDEM-X datasets and ICESat profiles (Semakova and Bühler, 2017). Glaciological mass balance measurements have been taken on the Barkrak Glacier since 2016 (Hoelzle et al., 2017). In this study, the main objectives are to analyze the trend of glacier area change in the basin and specify mass balance estimations using new data and approaches.

## 2. Study Area

The study area mostly includes small glaciers (up to 3 km<sup>2</sup>; in average they are less than 0,5 km<sup>2</sup>) around the upper reaches of the Oygaing and Maydantal Rivers, which are the main tributaries of the Pskem River (Figure 1). It is a right-hand component of the Chirchik River that is the feeder of the Sir-Darya River. The maximal part of glacierized area (36.4%) falls within elevation zone of 3600-3800 m. The elevation zone higher than 4000 m includes 2.2% of the glacierized area. Most of the glaciers belong to Corrie type with no debris cover. On the basis of ALOS/AVNIR-2 satellite data (2007-2010), there have been discovered 320 glaciers with a total area of 93.626 ± 2.9 km<sup>2</sup> (± 5.6%) (Semakova et al., 2016). By that period, the area had decreased by

23% since the First Inventory (refined data) in 1957 (Schetinnikov, 1976). That analysis was done for the glaciers described in the Catalogue of Glaciers (Schetinnikov and Podkopaeva, 1968). The retreat rate per year in the area fairly decreased from the 1978-1980s (Schetinnikov, 1997) to the 2007-2010s.

## 3. Data and methods

We considered all reasonable cloud-free quality Landsat and Corona / KH-9 acquisitions for the years with minimal seasonal snow cover on the dates of the end of the ablation season from the USGS service archive.



Figure 1: Location of the study area

Finally, we selected 10 images for 1973 (KH-9, 6-9 m resolution), 1977 (Landsat MSS, 60 m resolution), and 2000, 2006, 2011, 2013, 2014, 2017, 2018, 2020 (Landsat - 5 / 7 / 8, 30 m resolution) which covered the whole study area. Almost all images since 2000 were pan-sharpened due to the pan-chromatic band (15 m). We manually digitized the outlines of glaciers for every period including the remnants of disintegrated glaciers and the perennial small-sized snowfields that do not show any bare ice, given they can be seen on all analyzed images, even if they are not listed in the catalogues of 1957 and 1978 (Schetinnikov, 1997, Schetinnikov and Podkopaeva, 1968).

The error of location of the glacier is about half a pixel resolution (7.5 m for images since 2000). A mean relative error for glaciers for the area of 0.01 km<sup>2</sup> is 19%, for the area of 0.1 km<sup>2</sup> it is 6%, for the area of 0.5 km<sup>2</sup> - 3%, and for 1 km<sup>2</sup> it is 2%. The accuracy is worse for the Landsat MSS image because of the pixel size. The image of KH-9 is the scanned photograph; it was geo-referenced to the orthorectified Sentinel 2A image with 1C processing level to have the accuracy no worse than the Sentinel resolution (10 m). We considered also Corona images for 1960, 1963, 1966, and 1968, but they did not fully cover the basin, and due to high geometric distortions and georeferencing errors we excluded them from further analysis. There is a gap in data between 1977 and 2000; the reasonable cloud-free images are available for 1993, 1996 and 1998 from the Landsat 4-5 TM Collection but increased snow-covered area in the mountains for

those years did not allow us to use them in trend analysis.

We also considered all historical materials related to the study area including aerial photographs from 1942, as well as maps from 1958 and 1989. Preferring to deal with the first source, we selected 7 aerial photographs that covered 54 glaciers in the basin and 17 glaciers outside the basin behind the Talas Ridge. The images were georeferenced with affine and mostly spline transformation to the Landsat image for 2020 using from 26 to 48 control points located on the bends of rivers and ridges. During the processing we concentrated rather on the big-sized glaciers than on the small-sized ones. The next step was digitizing the boundaries of all glaciers and calculating their area.

To consider glacier elevation changes, we used the geodetic method based on the differencing of multi-temporal DEMs (Digital Elevation Models). Input data were TerraSAR-X /TanDEM-X interferometric data of the Single Look Slant Range Complex (SSC) product type (complex radar images with amplitude-phase parameters in the slant range geometry) that were acquired in a bistatic InSAR strip-map mode with single polarization (HH). The DEMs with an extent of ~30 km × 50 km were generated and post-processed by two different ways. One of them included an interferometric processing of two datasets from a descending satellite pass on December 08, 2013 and on February 01, 2014 covering some glaciers of the Oygaing River basin by using a standard workflow in SARscape software.

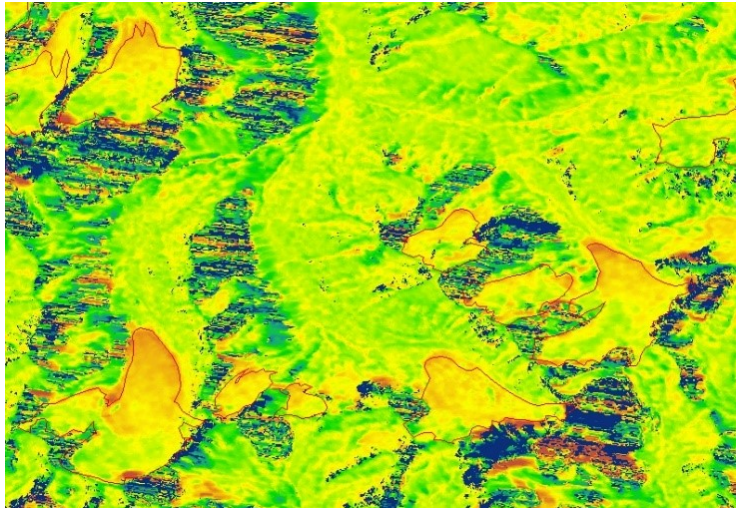


Figure 2: Glaciers of the Oygaing River basin on the phase unwrapping image

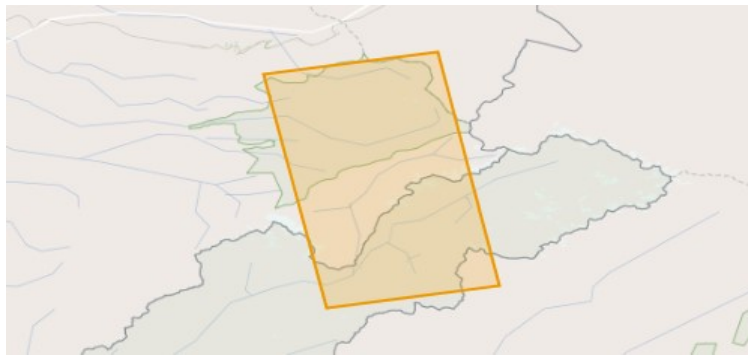


Figure 3: Data coverage of the study area with the ITP processing

The obtained single DEM scenes were coregistered with SRTM-1 and other DEMs which were generated earlier on the dates of February 19, 2012 and November 23, 2011 (Semakova and Bühler, 2017) using reference GLAC/ ICESat laser altimetry data. The unwrapping process of differential phases during the InSAR technique processing detected the errors on the steep slopes that is typical for the radar acquisition in the mountains, however, the surface of glaciers is generally not affected by the artefacts (Figure 2).

The second way was the using of the Integrated TanDEM-X processor (ITP) which was developed in DLR specially to process such type of data and allowing full control over the whole processing scene and byproducts (Rizzoli et al., 2017 and Rossi et al., 2012). Advanced techniques were applied to reduce areas affected by phase unwrapping in complex topography regions like the surrounding glaciers area as well as the accurate derivation of absolute elevation of the DEMs (Lambrech et al., 2018). Input data were datasets for the February 8,

2012 and March 8, 2014 (Figure 3) with the ascending orbit direction and similar parameters of acquisitions, the global TDM DEM as a reference, NASADEM version of SRTM, and Landsat-7 ETM+ for September 24, 2012. The plains on the North of the study area served as reference data for the vertical coregistration. In the result of the processing, we revealed large areas affected by phase unwrapping errors, including the phase discontinuity, radar shadows, and layover area in the complex topography ranging from 770 to 4232 m a.s.l within a strip map scene for 2012 (Figure 4). This situation did not improve when we used an additional dataset of the opposite geometry for February 1, 2014.

It is clear, that the site configuration (glaciers confined in narrow watersheds surrounded by steep slopes) and its aspect was not suitable enough in relation to the azimuth flight direction. The glaciers size has not compensated for the impact of layover and shadow effects because of the SAR imaging side view.

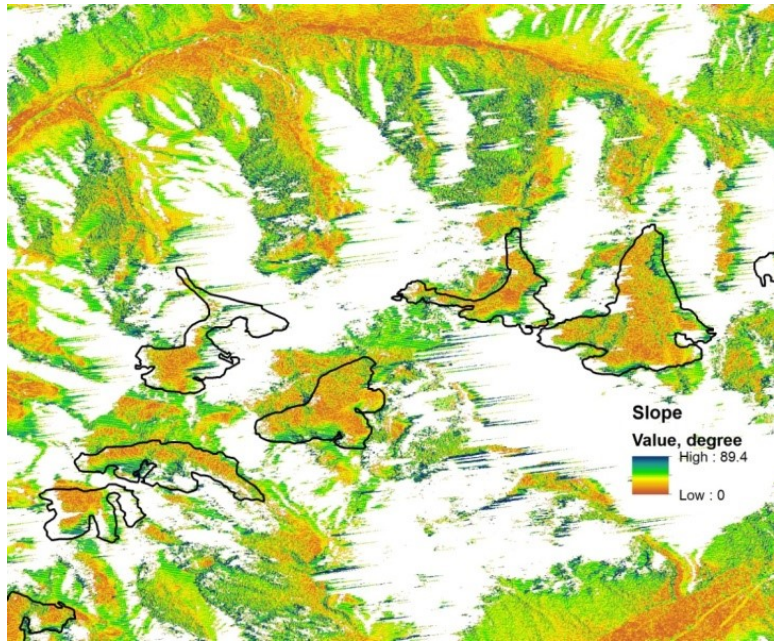


Figure 4: Glaciers located on the southeastern part of the Maydantal Ridge. Large area with the voids is the area with the phase unwrapping errors on the steep slopes

However, a possible signal of glacier elevation change was revealed there. Despite some missing coverage at the borders of the glaciers, we analyzed differences between the generated DEMs for the plains that are outside the mountainous area and for the parts of the glacier surface covered by data. Finally, we considered tendency of climate characteristics in the region and related glacier changes.

#### 4. Results and Discussion

To consider glacier area changes since 1942, we analyzed a total area of 22 glaciers in the Pskem River basin, their size being more than 0.3 km<sup>2</sup> for that period. The biggest glacier was 3.65 km<sup>2</sup> (Figure 5). It is clearly seen that the glacier boundaries and terminus positions, particularly, have changed significantly since 1942; area of the glaciers have been gradually decreasing; some of them disintegrated into two or even three parts by 2020. The change in area is 20% for 78 years. Concerning the glaciers located behind the Talas Ridge (their runoff does not belong to the Pskem River basin), we analyzed the area of 14 glaciers, their size being more than 0.3 km<sup>2</sup>. Their total area has decreased by 25% by 2020. The difference in changes is most likely due to the microclimatic and orographic factors in the region. Considering the glaciers changes in our study area in all investigated periods, we should note that their area in 1942 is

slightly less than the area in 1973 (Figure 6), however, the image for 1973 was free from seasonal snow that could overestimate the area. It could probably be caused by cyclical changes in glaciation when glaciers move from one stationary state to another one under the influence of climatic changes; or it can be caused by too small a statistical sample for the analysis.

Considering all glaciers in the Pskem River basin for 1960s and 1970s and comparing them with the catalogues data for those periods, we found that the number and area of glaciers taken on the basis of used satellite data significantly exceeds the catalogues data for 1957 and 1978. Differences in area between a merged image of 10 m resolution generated from the Corona satellites imagery for 1960, 1963, 1966 and 1968 and the Catalogue data for 1957 is about 10 km<sup>2</sup> (8%), the Landsat MSS data for 1977 and Catalogue data for 1978 is 19 km<sup>2</sup> (15%), the Corona and KH-9 (1973) images is 5%. As a result, to consider the glacier area change in the region, we used homogeneous data taken from the images that covered the whole basin on the date of acquisition and processed by our unified method of digitizing the glacier boundaries. Although the visual perception of the monospectral KH-9 image is different from multispectral Landsat images, we chose the data of 1973 as the basis point from which we considered glacier area changes for the whole basin.

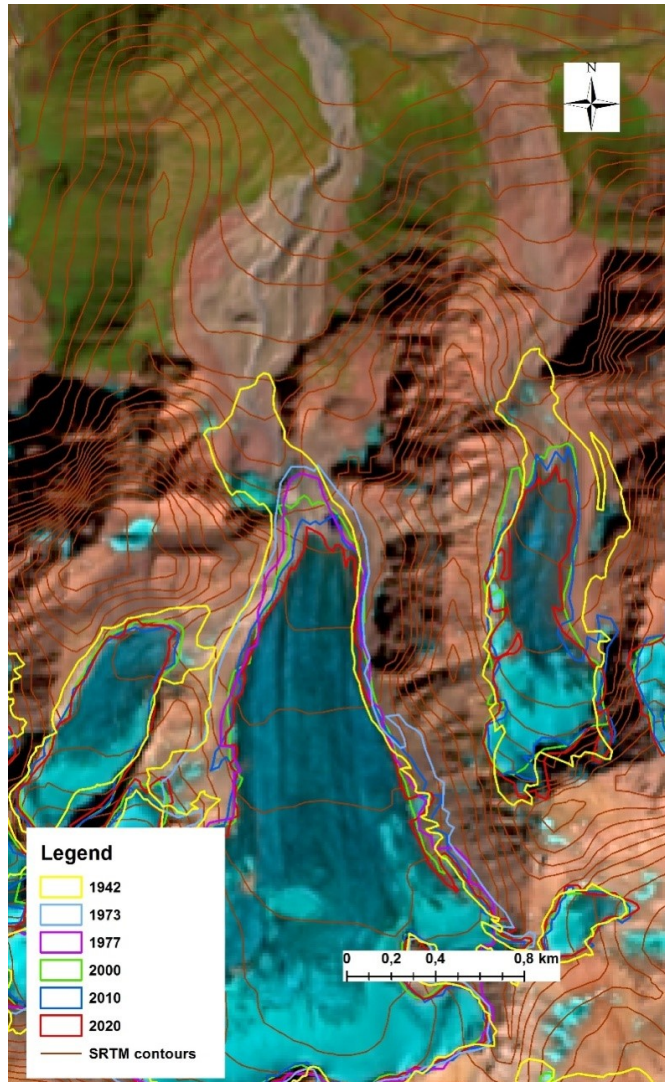


Figure 5: Glacier area changes since 1942 on the Landsat image of 2020

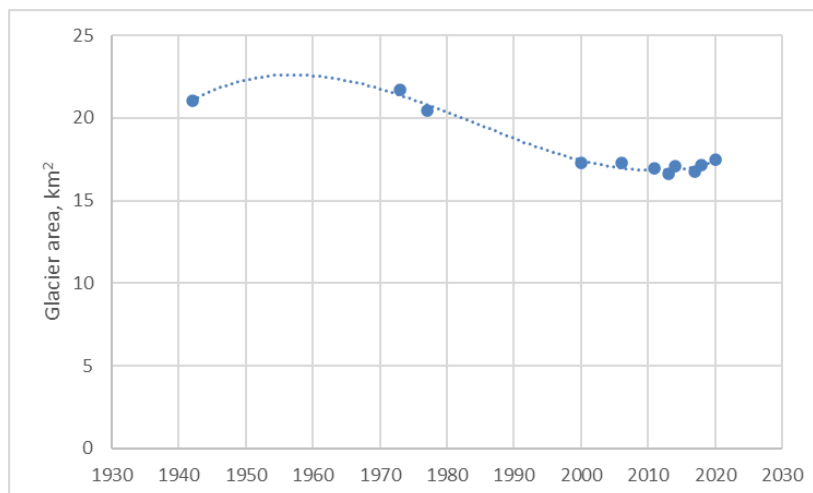


Figure 6: Total area of 22 glaciers in the Pskem River basin since 1942 to 2020

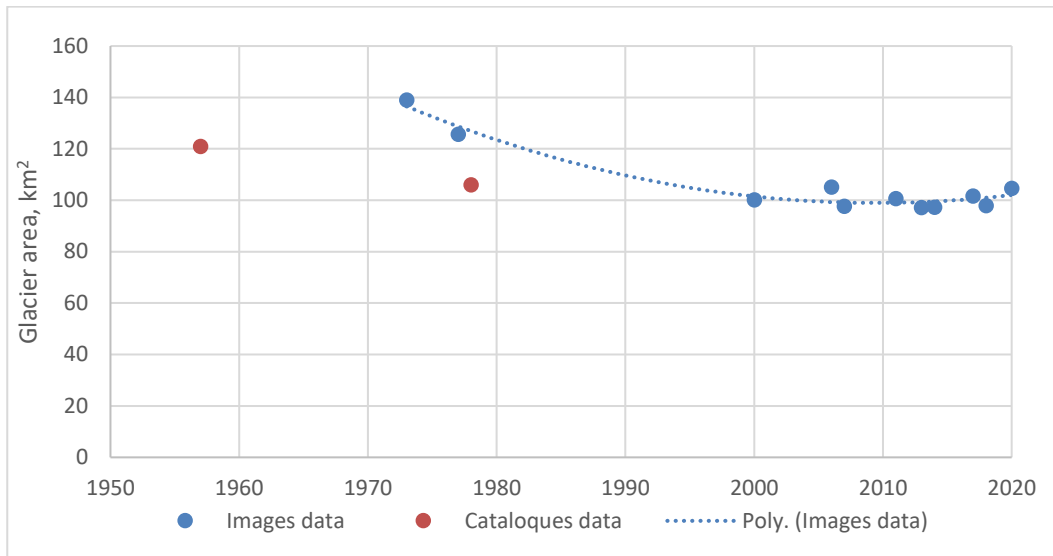


Figure 7: Total area of all glaciers in the Pskem River basin for different years

Distribution of the studied glaciers in total area for the different periods is shown on the Figure 7. There is a polynomial trend of glacier area change with a correlation proportion of 0.95. Since 2000, there have been no significant changes taking in account the accuracy of the total area of glaciers in the basin that was calculated as the sum of all errors for the glaciers in the basin. For the Landsat pan-sharpened images it is  $\pm 4.6 \text{ km}^2$  ( $\pm 8.5\%$ ), for the Landsat 5 TM image (30 m resolution) it is  $\pm 11.7 \text{ km}^2$  ( $\pm 19.1\%$ ), for the Landsat MSS image it is  $\pm 19.6 \text{ km}^2$  ( $\pm 26.9\%$ ), and for the KH-9 image it is  $\pm 1.8 \text{ km}^2$  ( $\pm 1.9\%$ ).

In average, the glaciers area is  $100.2 \text{ km}^2$  for the period of 2000-2020 while the minimal area is  $97.1 \text{ km}^2$  in 2013;  $97.3 \text{ km}^2$  in 2014 and  $97.8 \text{ km}^2$  in 2018, and the maximal area is  $105.1 \text{ km}^2$  in 2006 and  $104.6 \text{ km}^2$  in 2020. We added the point of the ALOS / AVNIR-2 data for 2007-2010 (Semakova et al., 2016) taking into account 23 small glaciers with an average area of  $0.078 \text{ km}^2$  and total area of  $4.0 \text{ km}^2$ , which were in shadows or covered by clouds in those images. We retrieved the gaps from the Landsat data of neighboring years and removed 6 glaciers which were not found on other images. The total area became equal to  $97.7 \pm 3.1 \text{ km}^2$  ( $\pm 5.6\%$ ) for that period. There is a linear negative trend in area from 1973 to 2000 with a correlation coefficient of 0.96. The number of glaciers was increased as a result of their disintegration in the warming conditions for that period; the warmest and driest period was the period of 1971–1980 from the studied 1961–1990 (Glazirin and Tadjibaeva, 2011). The largest number of glaciers is in a size class of  $0.1\text{-}0.5 \text{ km}^2$ . By 2020, they occupy 43% of the total

number and 26% of the total area of glaciation. Almost as much, 38% of all glaciers are less than  $0.1 \text{ km}^2$  in size; they are 6% of the entire glaciated area. The glaciers larger than  $1 \text{ km}^2$  in size compose 9% of the total number and 48% of the total area.

For such glaciers, that are more than  $1 \text{ km}^2$  in size, a rather approximate estimation of the elevation change was carried out. Most glaciers have a flat surface. For that surface, the mean lowering rate was almost the same in both cases; for the Oygaing glaciers it was a bit higher, until  $1 \text{ m/y}$  from 2012 to 2014. The mean value of the DEMs differences on the plains in the north of the scene (Figure 3) is  $-0.17 \text{ m}$  (2014 – 2012);  $-0.57 \text{ m}$  (2014 – 2000);  $-0.41 \text{ m}$  (2012 – 2000), hence all DEMs were co-registered with good quality. The mean value of the differences (2014 – 2012) in average for 10 glaciers is  $-1.35 \pm 7.81 \text{ m}$  for 2 years; Min value is  $-2.38$ ; Max value is  $-0.31 \text{ m}$ .

All acquisitions were made in the same season; hence a radar signal penetration depth error is minimal in this case. The given size of the glaciers allows to consider a rough estimation of mass loss only. So, a mean surface lowering rate is  $-0.68 \pm 3.91 \text{ m/y}$  from 2012 to 2014. Annual mass balance is  $-1.08 \text{ m w.e.}$  for that period, and glacier mass loss is  $932.7 \text{ kt/y}$ . Possible errors can be related to the glacier boundary and elevation identification, and an ice density assumption is  $860 \text{ kg/m}^3$ . These estimations are close to our previous findings (Semakova and Bühler, 2017). Verification with new satellite data and comparison with the field measurements at the Barkrak Glacier (Hoelzle et al., 2017) will allow to get more reliable current assessments in glaciers mass balance in the region.

Thus, despite the fact that since 2000 the total area of glaciation in the basin has some stability, the size of individual glaciers in area, their thickness and mass balance can change in different ways, depending on the precipitation sum and summer air temperature in separate years, location of glaciers in certain elevation and aspect zones, and orographic conditions. Considering long-term observations in air temperature and precipitation sum on the Oygaing meteorological station located on 2.15 km elevation in the region, one can see the following (Figures 8 and 9). Linear trends of average annual air temperature (T yr) and average summer air

temperature (T VI-VIII) for June, July and August for the period of 1963-2018 are positive, however, the coefficient of (T yr) trend is higher than the coefficient of (T VI-VIII) trend which specifies that the warming occurs mainly due to the rise in winter and spring temperatures and not due to the changes in summer temperatures. Another favorable condition for glaciers is increasing precipitation in winter months (Figure 9). It is known that the most extreme snow year in Central Asia was 1969 which affected the snowiness of glaciers. The digitization of the upper part of the glaciers for those years was carried out almost along the very ridge.

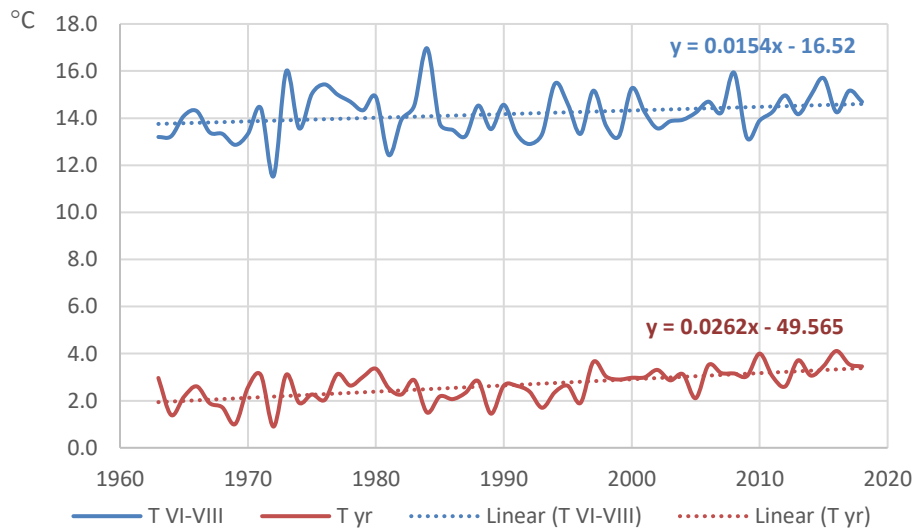


Figure 8: Linear trends of average annual air temperature (T yr) and average summer air temperature (T VI-VIII) on the Oygaing meteorological station for the 1963-2018 period. The trend coefficient is a characteristic of the average rate of temperature change over the considered period

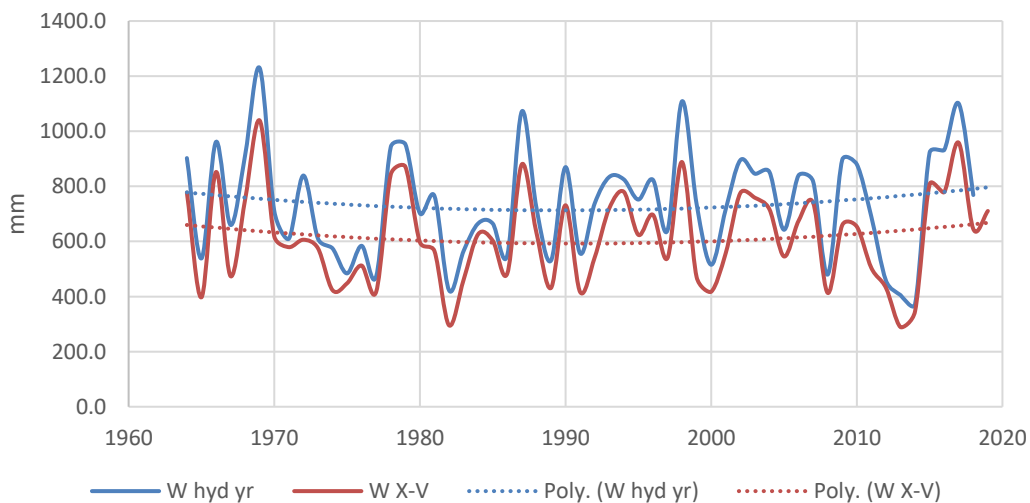


Figure 9: Polynomial trends of precipitation sum for hydrological year (W hyd yr) and for winter period (W X-V) from 1963 to 2018-2019

Minimum precipitation sum was in 2013 and 2014; the glaciers area was also minimum in those years and mass loss reached high values. Precipitation sums for a hydrological year, from October to October, was taken as the annual precipitation sum in the analysis. Its trend is the same for winter precipitation sum from October to May. The selected polynomial trends better describe the situation that is currently observed in the Pskem River basin. It is known that the glaciation of the basins is constantly changing, adapting to new climatic conditions, after which it passes into a new stationary state. Further inventories of glaciers will make it possible to refine the estimates obtained and to reveal the duration of a particular state of glaciation in the Pskem River basin.

## 5. Conclusion

The values of the glacier area and elevation change are important to estimate the hydrological regime change downstream, as well as the climate change at the altitudes where there are no hydrometeorological observations done currently. In this research, we estimated the changes in area for 22 glaciers since 1942 and for all glaciers since 1973 in the Pskem River basin. The study area includes glaciers of the basins of all tributaries of the Pskem River, runoff from which enters the territory of Uzbekistan. Aerial photographs from 1942 and satellite data such as KH-9 from 1973 and Landsat data from various years of acquisitions were used to estimate the glacier area change for different periods up to 2020. We considered glaciers that were identified in all those images. It was revealed that there are no significant changes in the total glacier area since 2000 and glaciation is in a stationary state within the measurement accuracy. Current glaciation in area in the Pskem River basin is about 100 km<sup>2</sup>.

The single TanDEM-X CoSSC datasets are useful tools to estimate the glacier surface lowering rate. The selection of the relevant available datasets from EGP catalogue was made for the season of SRTM data. Analysis of the generated DEMs revealed a lot of phase unwrapping errors in the mountain area. However, we estimated the glacier mass loss on average for 10 glaciers using rather a flat non-steep surface of the glaciers. It was equal to 932.7 kt/y from 2012 to 2014, in the period when there was a minimum of precipitation. New satellite data for this area with better configuration of acquisitions will allow to clarify the results.

## Acknowledgements

The authors are grateful to Remote Sensing Technology Institute (IMF) of the German Aerospace Centre (DLR) and the DAAD foundation

for the opportunity to perform InSAR research at the SAR Signal Processing Department. Special thanks to Dr. Dana Floricioiu and Dr. Lukas Krieger for the valuable support in data processing with the Integrated TanDEM-X processor and kind assistance during the work. Data processing in ENVI SARscape software were performed thanks to institutional Grant (SNF SCOPES IZ74Z0\_160463/1) of the Institute of Geology and Geophysics which was funded by SNF (Swiss National Science Foundation). TanDEM-X data were kindly provided under DLR proposals number XTI\_GLAC6758 and DEM\_GLAC1503. Landsat, KH-9, and SRTM data were obtained from the United States Geological Survey (USGS) archive.

## References

- Glazirin, G.E. and Tadjibaeva, U.U., 2011, *Izmeneniya klimata v visokogorye Sredney Azii v kontse XX veka (Climate Change in High Mountains of Central Asia in the Late of Twentieth Century)*. *Ice and Snow Journal*, Vol. 114(2), 12–15.
- Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkushkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usabaliev, R., Vorogushyn, S., Yakovlev, A. and Zemp, M., 2017, Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. *Geoscientific Instrumentation, Methods and Data Systems*, Vol. 6(2), 397–418. <https://doi.org/10.5194/gi-6-397-2017>.
- Kudyshkin, T., Tarasov, Y. and Yakovlev, A., 2014, *Izmenenie oledneniya rechnih basseynov s preobladaniem malih lednikov vo vtoroy polovine XX – nachale XXI veka (Changes in the Glaciation in the River Basins with a Predominance of Small Glaciers in the Second Part of XX and in the beginning of XXI Century)*. *Issues of Geography and Geoecology*, Vol. 4, 45–54.
- Lambrecht, A., Mayer, C., Wendt, A., Floricioiu, D. and Völksen, C., 2018, Elevation Change of Fedchenko Glacier, Pamir Mountains, from GNSS Field Measurements and TanDEM-X Elevation Models, with a Focus on the Upper Glacier. *Journal of Glaciology*, Vol. 64(246), 637–648. <https://doi.org/10.1017/jog.2018.52>.
- Rizzoli, P., Martone, M., Gonzalez, C., Wecklich, C., Borla Tridon, D., Bräutigam, B., Bachmann, M., Schulze, D., Fritz, T., Huber, M., Wessel, B., Krieger, G., Zink, M. and Moreira, A., 2017, Generation and Performance Assessment of the

- Global TanDEM-X Digital Elevation Model. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 132, 119–139. <https://doi.org/10.1016/j.isprsjprs.2017.08.008>.
- Rossi, C., Rodriguez Gonzalez, F., Fritz, T., Yague-Martinez, N. and Eineder, M., 2012, TanDEM-X Calibrated Raw DEM Generation. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 73, 12–20. <https://doi.org/10.1016/j.isprsjprs.2012.-05.014>.
- Schetinnikov, A.S., 1976, Ledniki basseyna reki Pskem (Glaciers of the Pskem River basin). Gidrometeoizdat.
- Schetinnikov, A.S., 1997, Morphologiya oledeneniya rechnik basseinov Pamiro-Alaya po sostoyaniyu na 1980 god (spravochnik) (Morphology of Glaciations of Pamiro-Alay River basins as of 1980 (reference book)). SANIGMI.
- Schetinnikov, A.S. and Podkopaeva, L.D., 1968, Catalog lednikov SSSR (Catalogue of glaciers of USSR). Vol. 14 (1, 3). Gidrometeoizdat.
- Semakova, E. and Bühler, Y., 2017, TerraSAR-X/TanDEM-X Data for Natural Hazards Research in Mountainous Regions of Uzbekistan. *Journal of Applied Remote Sensing*, Vol. 11(03), 1-22, <https://doi.org/10.1117/1.JR-S.11.-036024>.
- Semakova, E., Gunasekara, K. and Semakov, D., 2016, Identification of the Glaciers and Mountain Naturally Dammed Lakes in the Pskem, the Kashkadarya and the Surhandarya River basins, Uzbekistan, Using ALOS Satellite Data. *Geomatics, Natural Hazards and Risk*, Vol. 7(3), 1081–1098. <https://doi.org/10.1080/19475705.-2015.1023852>
- Sold, L., Huss, M., Machguth, H., Joerg, P. C., Leysinger Vieli, G., Linsbauer, A., Salzmann, N., Zemp, M., & Hoelzle, M., 2016, Mass Balance Re-analysis of Findelengletscher, Switzerland; Benefits of Extensive Snow Accumulation Measurements. *Frontiers in Earth Science*, 4. <https://doi.org/10.3389/feart.2016.00018>
- Zemp, M., Hoelzle, M., & Haeberli, W. (2009). Six decades of glacier mass-balance observations: A review of the worldwide monitoring network. *Annals of Glaciology*, Vol. 50(50), 101–111. <https://doi.org/10.3189/172756409787769591>.