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Brief communication:

The Influence of Climate Change on GLOFs in the Northern Tien Shan Mountains: A case study from the Ala Archa Valley

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Abstract

The role of climate change in driving glacier lake outburst floods (GLOFs) remains insufficiently understood. Therefore, the Adygene and Aksay Valleys, two tributary valleys of the Ala Archa Valley in Kyrgyzstan (Tien Shan Mountains), were selected as the study area, to investigate the relationship between climate change and the occurrence of GLOFs. For this purpose, climatological, glaciological, and remote sensing data were analyzed. Despite a significant warming trend of 0.25°C per decade from 1980 to 2019 in the Ala Archa Valley and a pronounced glacier retreat at the Golubin Glacier (average mass balance −314 mm w.e. yr^{-1} since 1969), GLOF frequency has declined from eight events in the 1960s to one in the 2000s, all occurring in the Aksay Valley. These findings contrast with studies linking climate change to more GLOFs. The comparison of the two tributary valleys revealed that differences in geomorphology, and particularly in internal glacier composition, are key factors behind the spatially uneven distribution and decline of GLOF events in the Ala Archa Valley. This study also found that climate change is creating the conditions for future GLOF activity, as glacier melt in the Adygene Valley has led to the formation of numerous new glacial lakes, which may outburst with a considerable delay.

1. Introduction

Glacier lake outburst floods (GLOFs) are among the most complex natural hazards in high mountain regions, as they are triggered by a multitude of interrelated factors (Taylor et al., 2023). GLOFs result from long-term climatic and geomorphological factors combined with short-term triggers (Falatkova et al., 2019; Zaginaev et al., 2019a). Rising temperatures, glacier retreat, and valley morphology influence lake formation and the potential for outbursts (Daiyrov et al., 2022). Their occurrence is closely linked to the dynamics and activity of the adjacent glaciers (Zhang et al., 2024). Glacial lakes exhibit different outburst risks depending on their specific geomorphological, hydrological, and geological characteristics (Falatkova et al., 2019; Zaginaev et al., 2019a). According to Falatkova et al. (2019), the main triggers of GLOFs include sudden mass movements, intense rainfall, rapid snowmelt, and earthquakes, which can destabilize or overtop lake dams. Additional triggers include drainage blockage, melting of ice lenses within dams, and cascading effects from previous GLOFs. This multifactorial nature makes it difficult to accurately predict GLOF events and to assess their response to climate change. In the scientific discussion on the drivers of GLOFs, the extent to which anthropogenic climate change influences the occurrence of these events remains a subject of contention (Harrison et al., 2018). Numerous studies identify climate change as the main driving factor behind the increase in GLOFs, as intensified glacier melt in many regions has led to the formation and growth of new proglacial lakes (Chen et al., 2024; Zhang et al., 2023; Zhang et al., 2024; Zhang et al. 2025; Zheng et al., 2021). However, a substantial body of scientific research has yielded contradictory findings, suggesting that other factors, such as geomorphology rather than climate change, determine the risk of GLOFs. These studies have even observed a decrease in GLOF events in some regions despite accelerated global warming (Carrivick and Tweed, 2016; Harrison et al., 2018; Veh et al., 2022; Veh et al., 2023; Zaginaev et al., 2019b). In high mountain valleys, some of which are densely populated, GLOFs pose a considerable hazard potential for infrastructure (Meyrat et al., 2024) and for the lives of people living in the immediate vicinity of glacial lakes (Taylor et al., 2023). The High Mountain Asia (HMA) region is particularly vulnerable to GLOFs. According to Taylor et al. (2023), more than 15% of the total population of Kyrgyzstan (approximately one million inhabitants) are directly affected by the risk of GLOFs. Since the 1950s, more than 70 catastrophic GLOF events have been documented on the territory of the Kyrgyz Republic (Kattel et al., 2020). The catastrophic GLOF of July 8, 1998, in the Shakhimardan River Valley on the border with Uzbekistan was the most severe GLOF event ever documented in Central Asia. More than 100 people lost their lives in the downstream part of this transboundary catchment, mainly in the Uzbek exclave of Shakhimardan (Zaginaev et al., 2019b). The

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northern Tien Shan Mountains are one of the most vulnerable regions in Kyrgyzstan due to the high frequency of GLOFs (Daiyrov et al., 2022). Therefore, it is crucial to determine the future risk of GLOFs in this region and to gain an insight into the actual factors affecting the occurrence of GLOFs. This study attempts to provide an answer to the complex question of the influence of climate change on GLOFs. For this purpose, both the climatic factors and the geomorphological factors influencing GLOFs, as well as the spatial and temporal occurrence of GLOF events in a specially selected study region, the Kyrgyz Ala Archa Valley, will be analyzed in detail.

2. Study Area

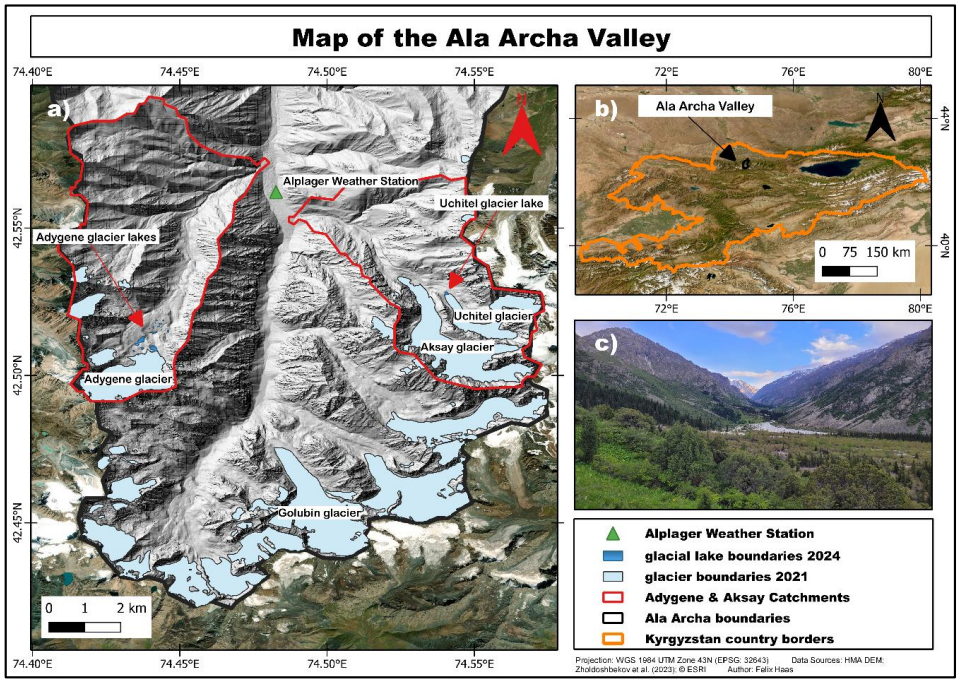

Fig. 1: Overview of the Ala Archa Valley. (a) Detailed map showing glaciers, glacial lakes, and boundaries of the Adygene and Aksay catchments, along with the location of the Alplager Weather Station. (b) Location of the Ala Archa Valley in Kyrgyzstan. (c) The lower part of the Ala Archa Valley in June 2024.

The research site of this study is located in the Ala Archa River basin in the Kyrgyz Ala-Too Range (Fig. 1), approximately 40 km south of the Kyrgyz capital, Bishkek. The Ala Archa River basin covers an area of approximately 270 km² (Zaginaev et al., 2019b). The average annual temperature at the Alplager Weather Station located 2,145 m a.s.l. was 2.9 °C between 1979 and 2013, while the average annual precipitation during the same period was around 560 mm (Zaginaev et al., 2019a). The climate in the Ala Archa Valley is continental, characterized by strong temperature fluctuations, both seasonally and within a single day (Kattel et al., 2020). The Ala Archa River Valley is oriented northward and has significant glaciation, which, although less extensive than in the central part of the Tien Shan, ranges from 33.3 km² (Bolch, 2015) to 31.45 km² (Zholdoshbekov et al., 2023). The Golubin Glacier is also located within the study area, covering approximately 5.42 km². This glacier extends from an elevation of about 3,300 m to 4,400 m a.s.l. (Azisov et al., 2022) and is the largest glacier in both the Ala Archa Valley and the entire Ala-Too Range. Notably, it is regarded as one of Kyrgyzstan's reference glaciers (Zholdoshbekov et al., 2023). Due to the continuous glaciological studies

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conducted from 1958 to 1994 and resumed in 2011, it plays a key role in documenting long-term glacier changes in the Ala Archa Valley (Azisov et al., 2022). To investigate the relationship between climate change and the occurrence of GLOFs, this study examines and compares two opposing tributary valleys of the main Ala Archa Valley, namely the Aksay and Adygene valleys.



Fig. 2: Proglacial lake located at the terminus of the Uchitel Glacier in the Aksay Valley, September 2024.

The catchment area of the Aksay River covers 28.3 km² (Zaginaev et al., 2016) and ranges from 2,200 m to 4,895 m a.s.l. (Meyrat et al., 2024). In 2017, the glacier area of the Aksay catchment was 8.5 km². The upper valley area contains two glaciers separated by a rocky ridge. The larger of the two glaciers is located on the western side of the valley and is known as the Aksay Glacier, while the smaller glacier to the east is known as the Uchitel Glacier (Zaginaev et al., 2019a). A proglacial lake (Fig. 2) is located in direct contact with the glacier tongue of the Uchitel Glacier at an altitude of 3,617 m (Meyrat et al., 2024). This lake is classified as a "moraine-dammed" lake and is primarily fed by meltwater from the glacier. Investigations conducted by Zaginaev et al. (2019a) revealed that the lake gradually formed in an intermorainic depression between 1988 and 1994. The Uchitel Glacier calves directly into the lake, generating ice cliffs that range from 15 to 25 m in height (see Fig. 2). Bathymetric surveys by Zaginaev et al. (2019a) estimated the lake's volume at approximately 27,000 m³ in 2016, with surface area varying from 6,733 m² in 2012 to 1,603 m² in 2015, and 4,870 m² in 2018. In addition, significant intra-annual variations in lake surface area have been observed, which were also documented in 2024 by direct field observations in July and September. Ice blocks along the shoreline (Fig. 2) indicate higher past water levels. The lake deepened from 12 m in 2012 to 13.9 m in 2018 due to the melting of buried ice at the lake's bottom (Zaginaev et al., 2019a). As the glacier lake continued to deepen into the moraine complex, discharge shifted from surface runoff in 2010 to entire subsurface flow by 2016, with water reemerging approximately 500 m downstream at 3,493 m a.s.l. At the confluence of the Aksay Valley with the main Ala Archa Valley, at an altitude of 2,200-2,350 m, there is a large and partially forested alluvial fan, evidence of past GLOF and heavy rainfall events (Zaginaev et al., 2016).

The catchment area of the Adygene River ranges between 37.9 km² (Zaginaev et al., 2019b) and 39.6 km² (Falatkova et al., 2019) and extends from an elevation of about 1,830 m to 4,200 m a.s.l. The glaciated area of the Adygene catchment is approximately 3.9 km², the majority of which is attributed to the Adygene Glacier (Falatkova et al., 2019). This 2.8 km² polythermal glacier is connected to a rock glacier composed of several sections of different origin. At the terminus of this glacier, a three-level cascade of proglacial lakes is present (Fig. 3), some of which are hydrologically interconnected, with additional seasonal lakes forming during the ablation period. (Falatkova et al., 2020). The cascade of proglacial lakes has formed within the last 50 years as a result of the ongoing retreat of the Adygene Glacier. The glacial lakes in the upper Adygene Valley are of different genetic types, including moraine-dammed and

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moraine-riegel lakes, as well as numerous thermokarst lakes of varying sizes (Falatkova et al., 2019). The studies by Falatkova et al. (2019, 2020) primarily focus on the investigation of three lakes located at the Adygene Glacier.



Fig. 3: Cascade of proglacial lakes located at the terminus of the Adygene Glacier in the Adygene Valley, September 2024.

The most studied glacial lake in the Adygene Valley, and by far its largest, is commonly known as the "Large Adygene Lake" or, in some cases, "Upper Adygene Lake". Its formation, similar to that of the Uchitel Glacial Lake, was driven by the development of a substantial intermorainic depression that formed in the 1960s and subsequently filled with meltwater from the Adygene Glacier. The lake, situated at 3,540 m a.s.l., had a surface area of approximately 31,900 m² in 2017 (Falatkova et al., 2020). Bathymetric studies revealed a maximum depth of 21.3 m and a volume of 210,000 m³ (Falatkova et al., 2019). Geophysical measurements have shown that the lake's dam consists partly of a weathering-resistant bedrock (riegel) and partly of loose, fragmented material and buried ice, classifying the lake as a moraine-riegel type with relatively stable development in recent years and minor volume fluctuations (Falatkova et al., 2019). The lake's drainage is predominantly through surface outflow, with occasional observation of subsurface drainage, primarily during periods outside the ablation season, as reported by Falatkova et al. (2020). Hydrologically, the lake is connected to the "Lower Adygene Lake" (see Fig. 15, No. 5).

The Lower Adygene Lake can be classified as a moraine-dammed type and is located approximately 90 m below the bedrock ridge (see Fig. 15, No. 4) of the Large Adygene Lake, at an elevation of 3,451.5 m a.s.l. This glacial lake is situated within a thermokarst depression, has a maximum surface area of 3,400 m² and a depth of 4.4 m and likely formed in the late 1980s (Falatkova et al., 2019). Its volume varies seasonally and diurnally, from 10,000 to 15,000 m³, and it completely dries out outside the ablation period (Falatkova et al., 2020). These fluctuations in the water level were also confirmed by direct observations at the beginning and end of the 2024 ablation period. The lake is entirely drained through subsurface flow and is likely fed not only by surface inflow from the Large Adygene Lake but also by subsurface channels connected to other glacial lakes (Falatkova et al., 2019).

Directly adjacent to the terminus of the Adygene Glacier, another glacial lake, also classified as moraine-dammed, has formed in recent years (see Fig. 15, No. 2). In literature, this glacial lake is most frequently referred to as the "Upper Adygene Lake". Situated at an elevation of 3,580 m a.s.l., the lake had a surface area of 16,020 m² and a maximum depth of 14 m in 2017 (Falatkova et al., 2020). This lake is characterized by extremely dynamic development in recent years. According to Falatkova et al. (2019), bathymetric measurements revealed a significant increase in depth, from 3.7 m in 2007 to 14 m in 2017. Similarly, the surface area expanded substantially, from 5,710 m² to 16,020 m² over the same period. By 2017, the lake's volume reached 106,000 m³. As with the Uchitel Glacial Lake, the continued deepening of the

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lake into the moraine complex led to a shift in drainage patterns. The lake now drains predominantly through subsurface flow, with surface runoff occurring minimally and only during periods of abundant meltwater availability. A portion of the water flows underground to the Lower Adygene Lake, contributing to its inflow. The lake's dam consists primarily of frozen glacial debris, with embedded ice lenses in certain areas, as demonstrated by ERT (Falatkova et al., 2019).

Numerous small lakes are present near the glacier terminus and at the elevation of the Lower Adygene Lake. Those in direct contact with the glacier tongue are highly dynamic, expanding with meltwater input but often drying out as the glacier retreats further (Falatkova et al., 2019). Smaller thermokarst lakes (Fig. 15, No. 6) at the elevation of the Lower Adygene lake are typically seasonal, drainless, and form in depressions created by dead ice within the rock glacier (Falatkova et al., 2020). Other non-stationary lakes exist in the Adygene catchment, mainly in the Teztor tributary (Erokhin et al., 2018), but this study focuses only on lakes in the Adygene main valley, compared with the Aksay Valley. Similar to the outlet of the Aksay River, the confluence of the Adygene River and the Ala Archa River is characterized by an alluvial fan, which is partially covered by vegetation (Zaginaev et al., 2019b).

3. Data and Methodology

Due to the geographical proximity of the Ala Archa Valley to the Kyrgyz capital Bishkek, the glaciers and climate of the valley were studied in detail at an early stage. Compared to other regions of Kyrgyzstan, the Ala Archa Valley therefore provides a good database, which was one of the reasons why the Ala Archa Valley was selected as the research area for this study. Furthermore, the Ala Archa Valley, with its extensive long-term GLOF records, serves as a pilot site for the GLOFCA project (Glacier Lake Outburst Floods in Central Asia), which aims to improve the understanding, monitoring and mitigation of GLOF hazards in Central Asia.

3.1 Meteorological Data from the Alplager Weather Station

The Alplager Weather Station, together with the Baitik Weather Station, is one of two stations in the Ala Archa Valley with long-term meteorological records. Since the 1970s, daily precipitation, air temperature, humidity, and solar radiation have been recorded at this site. The climate data from the Alplager Station were provided for this work by Azisov et al. (2022), who previously used this data to reconstruct the mass balance of the Golubin Glacier. Monthly temperature and precipitation records from 1980-2019 were analyzed to identify long-term climatic trends in the Ala Archa Valley and to assess their influence on glacier dynamics and glacial lake evolution in the two tributary valleys. Data processing was conducted using the statistical software R. Prior to analysis, the dataset was checked for gaps, outliers, and negative precipitation values to ensure data integrity. Temperature records for the Alplager Station were available from 1980 to 2019, while precipitation data were available only through 2018, as 2019 values were excluded due to gaps and measurement errors. Additionally, no temperature or precipitation data were available for 2011. Following data validation, absolute annual precipitation and temperature anomalies were computed. A 30-year reference period (1981-2010) was selected to calculate anomalies, enabling the detection of deviations from long-term averages and providing a basis for analyzing climatic trends in the Ala Archa Valley. In addition, long-term temperature and precipitation trends over the entire study period were calculated to evaluate climatic variability in the Ala Archa Valley. The results of the trend analysis were tested for statistical significance using a linear regression model. To evaluate glacier dynamics and glacial lake evolution during the ablation season, temperature trends were analyzed for the June-September period, which defines the ablation season in the Tien Shan mountains according to Barandun et al. (2021).

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3.2 Glaciological Data from the Golubin Glacier

The Golubin Glacier has been the subject of glaciological study since 1958 (some observations of the glacier's length change date back to 1861), but in situ measurements on the glacier were discontinued in 1994 and only resumed permanently from 2011 (Azisov et al., 2022). Nevertheless, extensive data on the glacier's mass balance and length changes are available, enabling this study to enhance understanding of glacier dynamics and glacial lake formation in the Ala Archa Valley. The glaciological data used in this study were obtained from two different sources: the publicly available World Glacier Monitoring Service (WGMS) database and modeled/reconstructed mass balance data for the Golubin Glacier provided by Azisov et al. (2022) for periods lacking in situ measurements of the glacier's mass balance. This study analyzed glacier length change data from 1861 to 2016 and annual mass balance records from 1969-1994 and 2010-2024. All data were obtained from the WGMS (2026) and are available at https://wgms.ch. The directly measured annual mass balance data was merged with the modeled mass balance data from Azisov et al. (2022) covering the gap period from 1994 to 2010. Azisov et al. (2022) reconstructed the glacier's mass balance for periods with missing measurements using a temperature-based model, which was calibrated with existing data and validated through glacier length changes and reanalysis climate data. All glaciological data were also analyzed and visualized using R software.

3.3 Current and Historical Remote Sensing Data

To analyze the evolution of glaciers and glacial lakes in the two tributary valleys of the Ala Archa Valley, this study utilized both historical and contemporary remote sensing data. Remote sensing data are essential for glacier monitoring, as in situ measurements are often impractical in remote glacial regions. In countries like Kyrgyzstan, direct glaciological measurements exist for only a small fraction of glaciers, further emphasizing the importance of remote sensing for glacier monitoring. Although the glaciers in the Aksay and Adygene valleys are relatively easily accessible via hiking trails, no glaciological measurements exist for the Aksay, Uchitel, or Adygene glaciers. This study focuses particularly on the Uchitel and Adygene glaciers, as their termini directly border glacial lakes.

To analyze changes in glacial lakes in the Adygene and Aksay valleys, declassified satellite images from the "Corona" spy satellite were used, specifically panchromatic Stereo Corona KH-4A and Corona KH-4B images from 1964 and 1971. The Corona satellite images used in this study were supplied in resampled form, with a resolution of 5 m. Both scenes were captured at the end of the ablation season in mid-September, resulting in minimal or no cloud cover over the glaciers or glacier forefields. The Corona data were provided by Bolch (2015), who used them in his study to map glacier outlines in the Ala Archa Valley and to generate a DEM to derive the geodetic mass balance of the valley's glaciers. Furthermore, the glacier outlines generated in his work were provided for this study to illustrate glacier changes in the Aksay and Adygene valleys. Zholdoshbekov et al. (2023) also provided glacier outlines for the Ala Archa Valley derived from Sentinel-1 SAR data and high-resolution drone imagery for 2021. Together, these datasets provide glacier outlines for the Aksay, Uchitel, and Adygene glaciers for the period 1964-2021. Using the historical satellite imagery and glacier outlines, detailed maps of the glaciers and glacier forefields in the Adygene and Aksay valleys were created in QGIS. In addition to historical satellite data, recent high-resolution remote sensing data were used to manually map the present-day extent of glacial lakes in the Adygene and Aksay valleys. Specifically, two PlanetScope satellite images from Planet Labs, available at https://www.planet.com/explorer/, acquired on August 9 and 26, 2024, were used. These images offer a high spatial resolution of 3 m. The high resolution of PlanetScope imagery is particularly well suited for mapping glacial lakes, as demonstrated by Daiyrov et al. (2022). Both PlanetScope scenes used in this study are cloud-free over the glacial lakes, ensuring clear visibility. By applying different false-color representations and band combinations, the glacial lakes were accurately mapped.

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To investigate the distinct geomorphology of the Aksay and Adygene valleys, longitudinal profiles were generated using the publicly available High Mountain Asia Digital Elevation Model (Shean, 2017), which offers a spatial resolution of 8 m and was downloaded for the study area via the NASA Earthdata search portal. The valley profiles were produced for the upper sections of both valleys. The resulting profiles are almost identical in length, with approximately 4.2 km in the Adygene Valley and 4.4 km in the Aksay Valley, thereby enhancing their comparability. Both profiles begin at the termini of the Adygene and Aksay glaciers at 3,613 m and 3,629 m a.s.l., respectively, ensuring that they start at nearly identical elevations and further enhancing their comparability. To highlight the geomorphological differences between the two catchments, knickpoints were identified in the profiles and these features were verified during several on-site field visits and examined in terms of their geomorphological characteristics. Furthermore, numerous camera and drone images of the glacial lakes, geomorphological features, and knickpoints in the two valleys were captured to illustrate the differences between the valleys and to document the lakes' spatial extent and current morphology.

3.4 GLOF Database

To illustrate the historical development of GLOFs in the Ala Archa Valley, a database of documented GLOF events in the HMA region was used. The database (HMAGLOFDB v1.3.0; Steiner and Shrestha, 2026) represents the first comprehensive compilation of GLOF events for the HMA region. It includes detailed information on the timing of events, lake formation and outburst processes, and downstream impacts. This GLOF database was filtered to extract documented GLOF events specific to the Ala Archa Valley. The recorded GLOF events in the Ala Archa Valley are based on historical records as well as on findings from Zaginaev et al. (2016) and Zaginaev et al. (2019b), who conducted dendrochronological analyses on alluvial fans in the valley to reconstruct past GLOF events. In this study, all documented GLOF events in the Ala Archa Valley were analyzed in detail using the statistical software R, with a focus on their timing, associated glacier catchments, and lake types.

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4. Results

4.1 Analysis of Meteorological Data from the Alplager Weather Station

The mean annual temperature at the Alplager Station from 1980 to 2019 was 3.09 °C. The following graph (Fig. 4) illustrates the results of the absolute annual temperature anomalies recorded at the Alplager Weather Station over several decades.

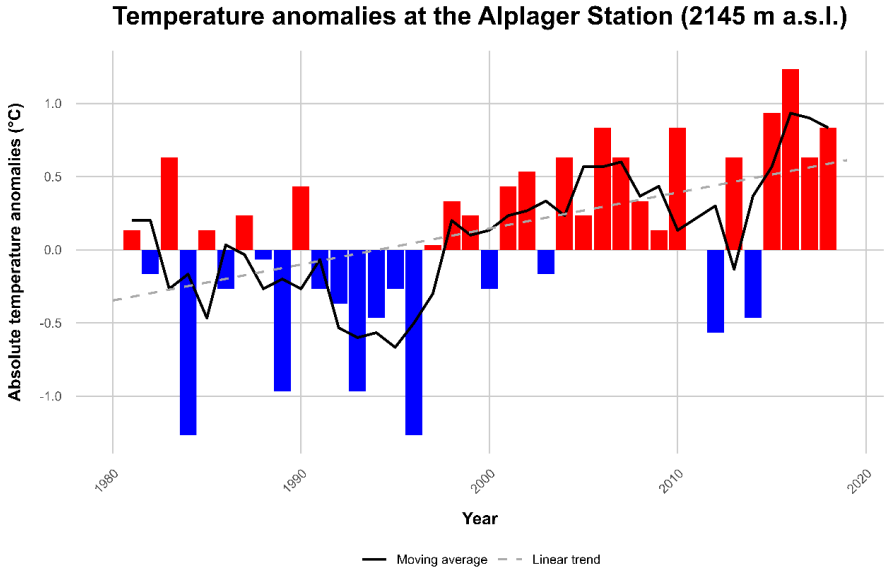

Fig. 4: Annual temperature anomalies (1980-2019) recorded at the Alplager Weather Station. Red bars indicate positive deviations in °C from the long-term average (1981-2010), blue bars represent negative deviations in °C. The black line shows the moving average, additionally the linear trend of annual temperatures is displayed as a dashed gray line.

The reference value for temperature anomalies is based on the average annual temperature from 1981 to 2010, which was 2.97 °C. Until the mid-1990s, most years were cooler than the long-term average. However, from the late 1990s or early 2000s onward, a period emerged in which most years showed positive deviations from the reference value. In recent years, temperatures have deviated significantly from the long-term average, in some years by more than one degree Celsius. The moving average further highlights the noticeable increase in positive anomalies over the past two decades, indicating intensified warming. The linear trend of annual mean temperatures also shows a continuous increase over time. Fig. 5 presents absolute temperature anomalies recorded at the Alplager Weather Station during the ablation period (June to September) over several decades. These anomalies represent deviations from the long-term average temperature for the ablation months. The reference value, based on the 1981-2010 average, was 11.26 °C.

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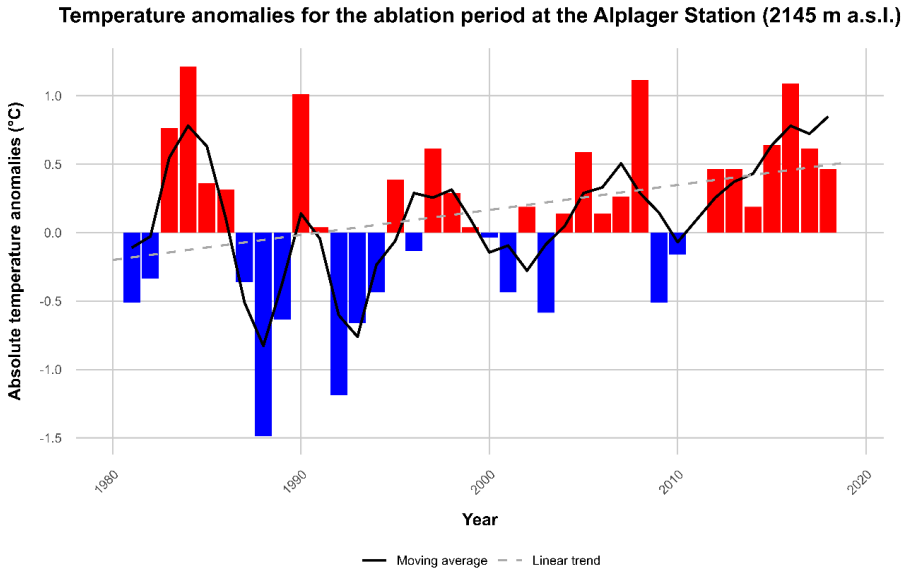

Fig. 5: Temperature anomalies (1980-2019) during the ablation period (June to September) recorded at the Alplager Weather Station. Red bars indicate positive deviations in °C from the long-term average (1981-2010), blue bars represent negative deviations in °C. The black line shows the moving average, additionally the linear trend of annual temperatures is displayed as a dashed gray line.

For the temperature anomalies during the ablation period, the Alplager Station exhibits a slightly different pattern compared to the annual temperature anomalies. Nevertheless, it is evident that predominantly positive deviations from the long-term average have occurred since the 2000s. Since 2010, exclusively positive anomalies have been recorded, indicating a pronounced warming trend during the ablation period. In the mid-1980s, temperatures during the ablation period also showed more positive deviations from the average, a trend that was not observed in the annual anomalies to this extent. Table 1 provides a more detailed overview of the linear trends in annual and ablation period temperatures at the Alplager Station.

Table 1: Comparison of Annual and Ablation Season Temperature Trends at the Alplager Weather Station (1980-2019), all values rounded to three decimals.

Trend Analysis at the Alplager Weather Station (2145 m a.s.l., 1980-2019)			
Time Period	Long-Term Average Temperature (1981-2010) [°C]	Temperature Trend [°C/year]	Temperature Trend P-Value
Annual	2.967	0.025	0.003
Ablation Season	11.261	0.018	0.040

The linear trends demonstrate a steady increase in average temperatures over time, both during the ablation period (Fig. 5) and in the annual mean (Fig. 4). The results of the trend analysis are statistically significant in both cases, as the p-value of the applied linear regression model is well below the commonly used statistical threshold of 0.05. The linear temperature trend for the annual average temperature shows an annual increase of 0.025 °C,

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resulting in a total warming of approximately 0.98 °C over the entire period from 1980 to 2019. In contrast, temperatures during the ablation period exhibit an annual increase of 0.018 °C, corresponding to a warming of 0.70 °C over the same period. Thus, warming during the ablation period was slightly lower than the annual warming. Furthermore, the temperature anomalies compared to the long-term average demonstrate that the warming trend has intensified over the last two decades, both on an annual basis and during the melt season.

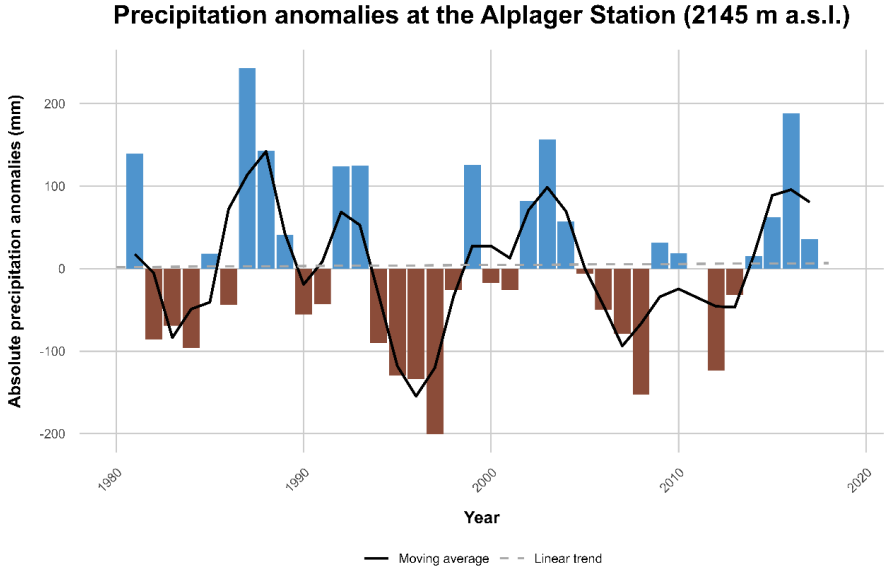

Fig. 6: Annual precipitation anomalies (1980-2018) at the Alplager Weather Station. Blue bars indicate positive deviations in mm from the long-term average (1981-2010), brown bars represent negative deviations in mm. The black line shows the moving average, additionally the linear trend of annual precipitation is displayed as a dashed gray line.

The average annual precipitation at the Alplager Station from 1980 to 2018 was 564.2 mm. Fig. 6 presents the absolute annual precipitation anomalies recorded at the station over several decades. These anomalies indicate deviations from the 1981-2010 reference period, where the average precipitation was 559.9 mm. In contrast to the temperature data, no clear long-term trend can be derived from the precipitation anomalies (Table 2).

Table 2: Precipitation Trends at the Alplager Weather Station (1980-2019), all values rounded to three decimals.

Trend Analysis at the Alplager Weather Station (2145 m a.s.l., 1980-2018)			
Time Period	Long-Term Average Precipitation (1981-2010) [mm]	Precipitation Trend [mm/year]	Precipitation Trend P-Value
Annual	559.923	0.123	0.935

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4.2 Results of the Glaciological Data Analysis

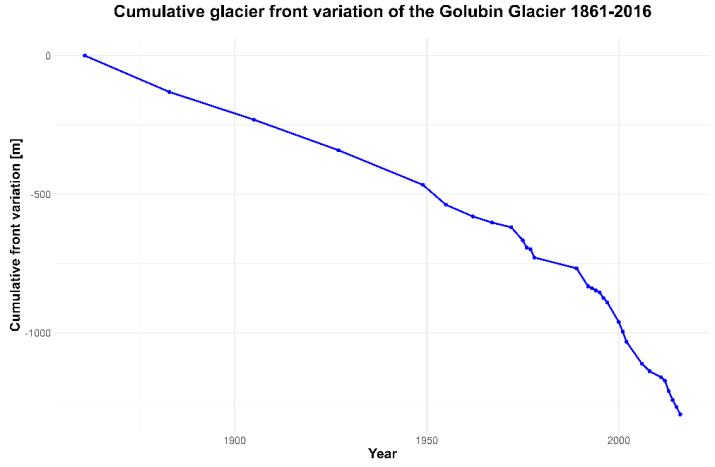

Fig. 7: Cumulative length change of the Golubin Glacier from 1861 to 2016.

Fig. 7 illustrates the cumulative length change of the Golubin Glacier (Fig. 8) from 1861 to 2016. The vertical axis represents the cumulative change of the glacier front in meters, while the horizontal axis represents the study period. It is evident that the Golubin Glacier has been continuously decreasing in length since records began in 1861. It is also noticeable that the retreat of the glacier front has accelerated since the 1950s, as indicated by the steeper slope of the graph. The length of the Golubin Glacier has decreased by more than 1,000 meters in total since records began, indicating significant glacier melt.



Fig. 8: The Golubin Glacier, August 2024.

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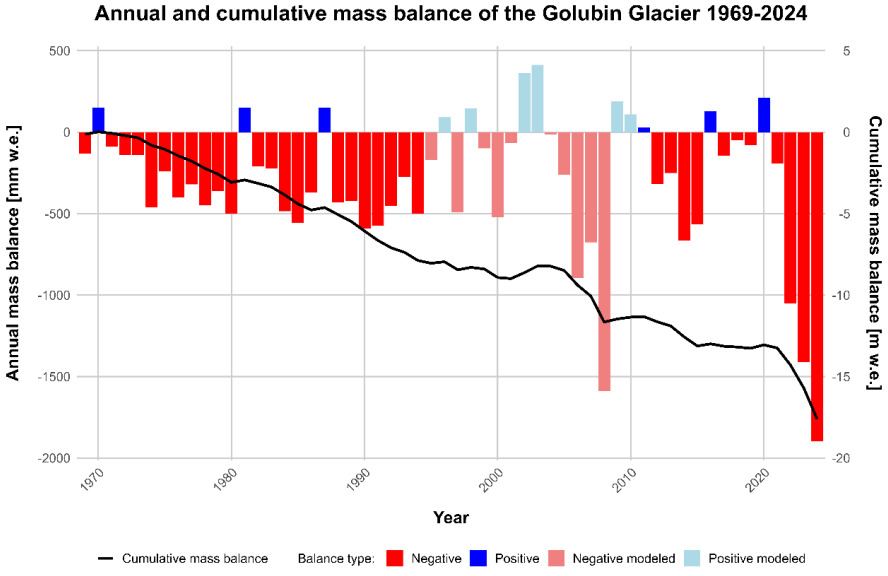

Fig. 9: Annual and cumulative mass balance of the Golubin Glacier from 1969 to 2024. Red and blue bars indicate measured negative and positive annual mass balance values in millimeters water equivalent (mm w.e.), while light red and light blue bars represent modeled/reconstructed values. The black line shows the cumulative mass balance in meters water equivalent (m w.e.).

Fig. 9 demonstrates the results of the annual and cumulative mass balance of the Golubin Glacier for the period from 1969 to 2024. The graph shows a predominantly negative mass balance of the Golubin Glacier since the start of glaciological measurements in 1969. Only a few years recorded a positive mass balance at all. The average mass balance was -314.4 mm w.e. yr^{-1} over the study period, or -353.2 mm w.e. yr^{-1} when considering only the directly measured mass balance values. By 2024, the total cumulative mass balance had amounted to more than -15 m w.e., indicating a significant mass loss of the Golubin Glacier. Furthermore, it is evident that years with strongly negative mass balances have increased since the 2000s, with values exceeding -1000 mm w.e. yr^{-1} in some cases. This underscores the acceleration of glacier melt at the Golubin Glacier in recent decades. Regarding the modeled mass balance data for the period from 1994 to 2010, a certain degree of uncertainty must be assumed. Nevertheless, the reconstructed mass balance data shows a similar trend to the measured annual mass balances, thereby confirming the pattern of pronounced glacier retreat of the Golubin Glacier during the study period.

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4.3 Changes in Glaciers and Glacier Forefields in the Adygene and Aksay Valleys

The following map (Fig. 10) illustrates the changes in the terminus of the Adygene Glacier between 1964 and 2021, as well as the formation of multiple proglacial lakes.

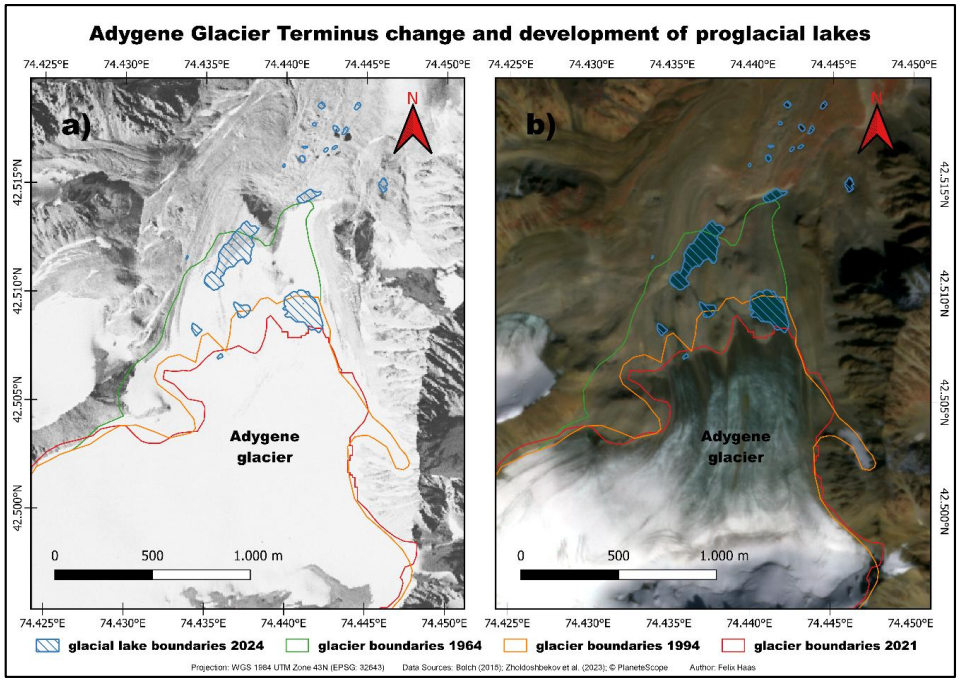

Fig. 10: Retreat of the Adygene Glacier (1964-2021) and formation of proglacial lakes at its terminus, visualized using multi-temporal satellite imagery: (a) Corona KH-4 panchromatic scene from 1964, showing the glacier's intact terminus prior to significant retreat. No proglacial lakes are visible.; (b) PlanetScope multispectral scene from 2024, highlighting significant glacier retreat and the emergence of a multi-stage proglacial lake cascade.

The Adygene glacier has retreated significantly since 1964, which can be clearly seen when comparing the Corona scene (a) from 1964 with the PlaneteScope scene (b) from 2024. A particularly significant retreat of the glacier tongue can be observed during the period from 1964 to 1994, followed by a further retreat until 2021. The PlanetScope scene also shows another slight retreat of the Adygene Glacier from 2021 to 2024. Fig. 10 clearly shows how a three-level cascade of proglacial lakes has formed at the site of the former glacier tongue. In the 1964 Corona scene, only a few small thermokarst lakes are visible near the rock glacier. The second map (Fig. 11) presents changes in the termini of the Aksay and Uchitel glaciers from 1964 to 2021, along with the formation of a proglacial lake at the terminus of the Uchitel Glacier.

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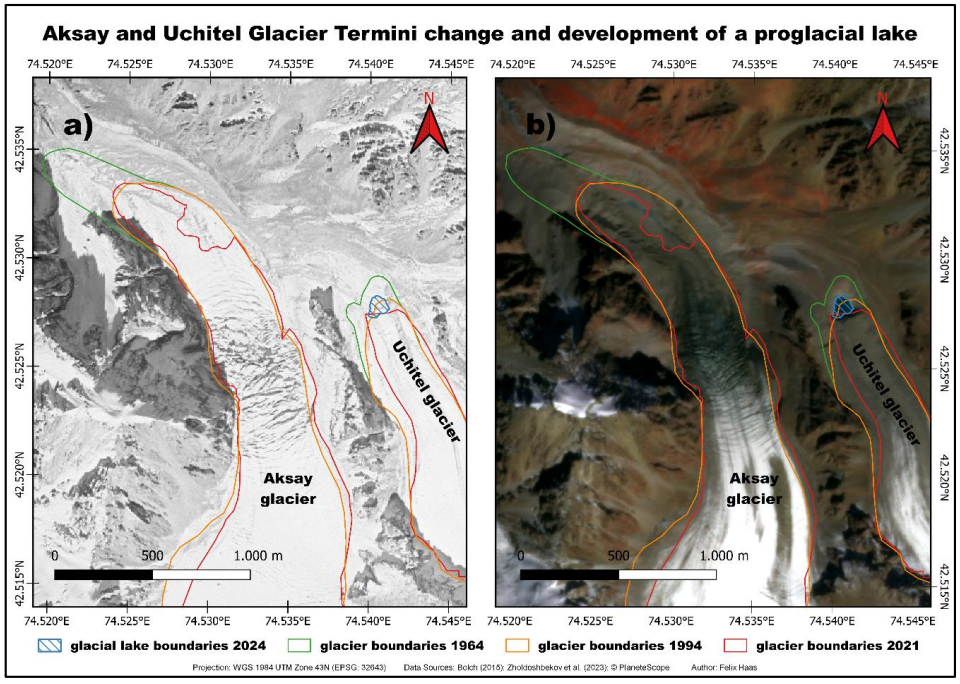

Fig. 11: Retreat of the Aksay and Uchitel glaciers (1964-2021) and formation of a proglacial lake, visualized using multi-temporal satellite imagery: (a) Corona KH-4 panchromatic scene from 1971, showing contiguous glacier termini with no visible lake; (b) PlanetScope multispectral scene from 2024, highlighting further glacier separation and significant expansion of the Uchitel proglacial lake.

Similar to the Adygene Glacier, the Uchitel Glacier experienced a significant retreat of its terminus between 1964 and 2021. This retreat is clearly visible in Fig. 11, where the glacier's extent has progressively decreased over the decades. The Aksay Glacier, on the other hand, exhibits a slightly different pattern of change. While a pronounced retreat occurred between 1964 and 1994, the glacier terminus remained at approximately the same elevation between 1994 and 2021, indicating a stagnation in its retreat. However, despite the stable terminus position, the Aksay Glacier experienced a noticeable reduction in width. Portions of its lateral terminus have diminished compared to previous decades, highlighting ongoing ice loss. Another notable change, visible in Fig. 11b, is the formation of a proglacial lake at the terminus of the Uchitel Glacier. In the 1971 Corona satellite scene (Fig. 11a), this lake is absent, with the area previously occupied by glacier ice.

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4.4 GLOF Database Evaluation Results

The following bar chart (Fig. 12) displays the number of documented GLOFs per decade in the Ala Archa Valley, categorized by glacial lake type.

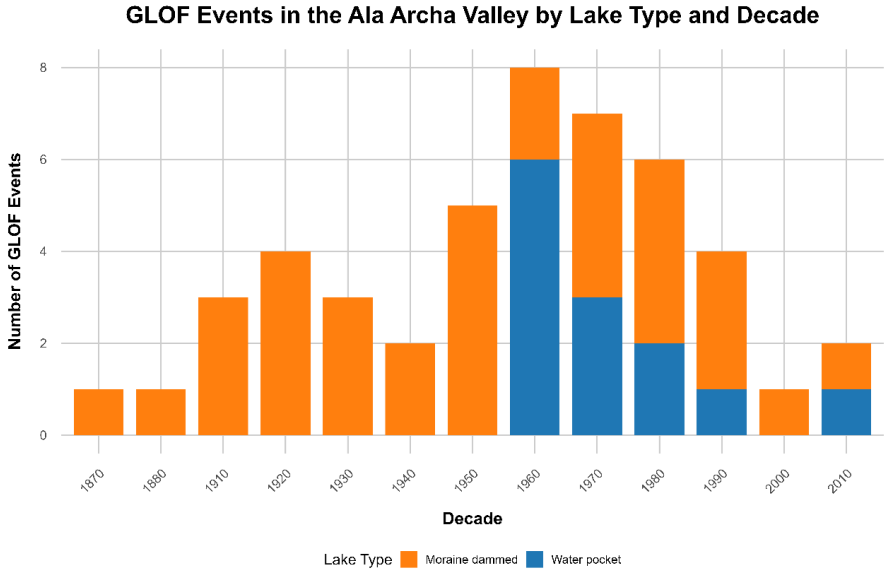

Fig. 12: Decadal frequency of documented GLOF events in the Ala Archa Valley by lake type (1877-2015).

A total of 47 GLOFs were documented in the Ala Archa Valley between 1877 and 2015. Over half of all GLOF events occurred between 1950 and 1980. A pronounced increase in GLOF frequency began in the 1940s, peaking in the 1960s with eight recorded events. Since the 1960s, however, the number of GLOFs has steadily declined, with only three events occurring in the last two decades.

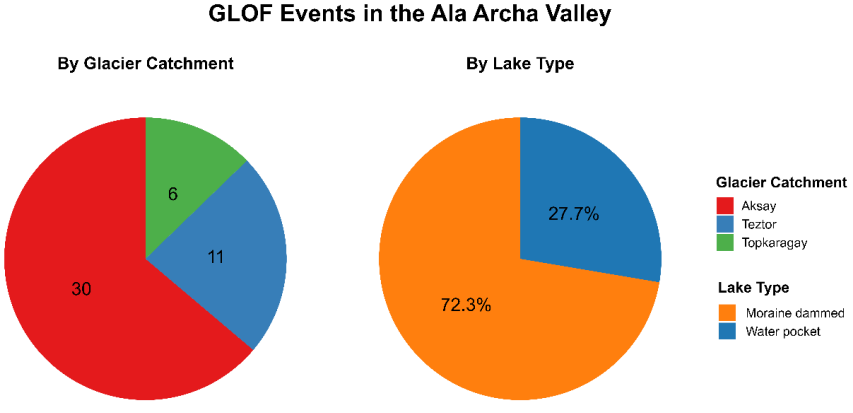

Fig. 13: Pie charts showing: On the left, the spatial distribution of GLOF events by glacier catchment and on the right, lake types of GLOF events in the Ala Archa Valley.

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The pie charts in Fig. 13 offer insights into both the origin of GLOF events within the Ala Archa Valley and the types of glacial lakes involved, shedding light on potential outburst mechanisms. The majority of documented GLOFs, 30 out of 47, originate from the Aksay Glacier's catchment, which also includes events likely triggered by the adjacent Uchitel Glacier (Zaginaev et al., 2016) due to their historical connection (Zaginaev et al., 2019a). An additional 11 GLOFs originate from the Teztor Glacier's catchment, while six events were documented in the Topkaragay Glacier's catchment. Remarkably, all 47 documented GLOFs fall into just two categories of glacial lakes: Moraine-dammed lakes and englacial water pockets, with nearly three-quarters linked to the moraine-dammed lake type.

4.5 Geomorphological Differences between the Adygene and Aksay Valleys

The two tributary valleys of the Ala Archa River examined in this study, the Aksay and Adygene valleys, exhibit distinct geomorphological differences. The map below (Fig. 14) illustrates these geomorphological characteristics and differences, along with longitudinal valley profiles of the upper, approximately 4 km long sections of the Adygene and Aksay valleys. Fig. 15 summarizes the geomorphological features of both valleys, including photographs and drone imagery.

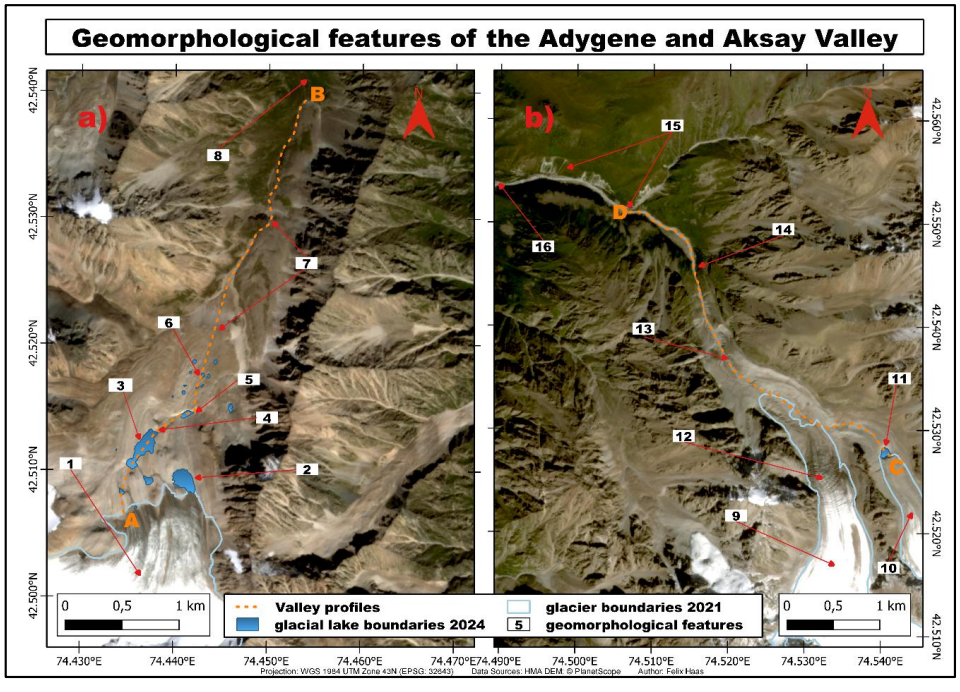

Fig. 14: Geomorphological features of the Adygene and Aksay valleys. (a) Overview of the Adygene Valley, showing valley profile A-B, glacier and glacial lake boundaries, and numbered geomorphological features. (b) Overview of the Aksay Valley, showing valley profile C-D along with glacier and glacial lake boundaries and identified geomorphological features.

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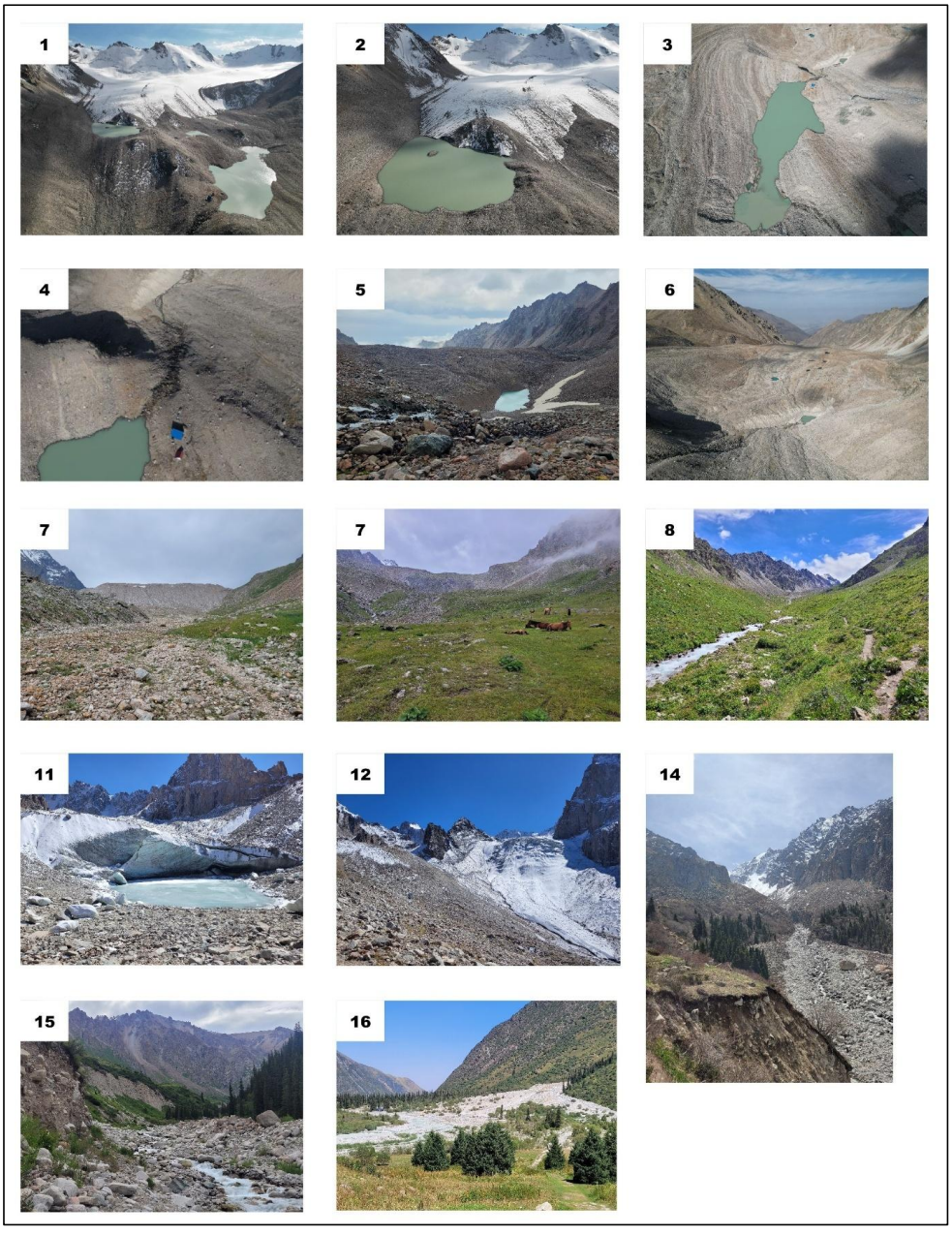

Fig. 15: Overview of key geomorphological features in the Adygene and Aksay valleys: **No. 1** Adygene Glacier, September 2024, **No. 2** Upper Adygene Glacial Lake, September 2024, **No. 3** Large Adygene Glacial Lake, September 2024, **No. 4** Moraine-bedrock riegel, September 2024, **No. 5** Lower Adygene Glacial Lake, July 2024, **No. 6** Rock glacier with thermokarst lakes, September 2024, **No. 7** Steep gradient knickpoints, July 2024, **No. 8** Beginning of glacial trough valley, July 2024, **No. 9** Aksay Glacier see Fig. 11, **No. 10** Uchitel Glacier see Fig. 11, **No. 11** Uchitel Glacial Lake, September 2024, **No. 12** Icefall of the Aksay Glacier, September 2024, **No. 13** Beginning of the canyon-like section of the Aksay Valley (no picture available), **No. 14** End of the canyon-like section of the Aksay Valley, May 2024, **No. 15** Kame Terraces, July 2024, **No. 16** Aksay Debris Cone, August 2024.

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Fig. 16 shows the longitudinal profile of the Adygene Valley, with geomorphological features marked along its course.

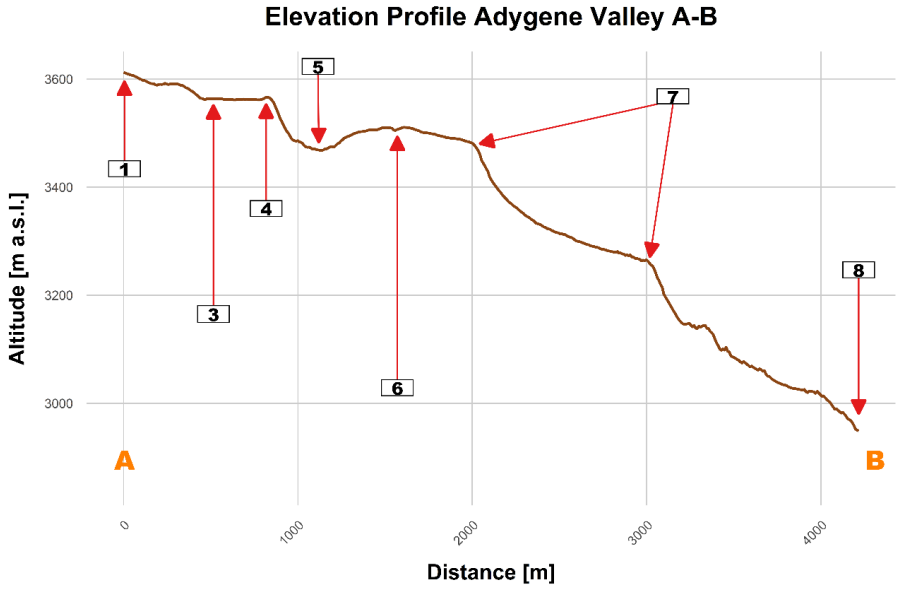

Fig. 16: Longitudinal profile A-B of the Adygene Valley with labeled geomorphological features.

The average slope of the Adygene Valley along the approximately 4.2 km long section A-B is approximately 9 degrees, with an elevation difference of about 664 m. The first section of the Adygene Valley, spanning approximately 2 km from the terminus of the Adygene Glacier (geomorph. Feature 1) and the cascade of proglacial lakes (geomorph. Features 2-5) to the first abrupt knickpoint (geomorph. Feature 7), has a very gentle gradient. Over this stretch, the elevation changes by only about 130 m. Between the two abrupt knickpoints, the slope increases, averaging 12.3 degrees over the approximately 1 km long section. The rock glacier, with its overlying thermokarst lakes (geomorph. Feature 6) disrupts the longitudinal profile of the Adygene Valley, causing regional increases in terrain elevation. Ruiz-Fernandes and Oliva (2019) situate the lower end of the rock glacier at an elevation of slightly below 3,000 m above sea level. Below the rock glacier, a glacial U-shaped trough valley (geomorph. Feature 8), a common feature in the Ala Archa Valley, exhibits a relatively gentle gradient (Ruiz-Fernandes and Oliva, 2019). After the confluence of the Teztor tributary valley with the Adygene Valley (not shown in the longitudinal profile), the slope increases again, and lateral moraines reappear. At the mouth of the Adygene Valley into the main Ala Archa Valley, a partially forested alluvial fan is present, similar to that of the Aksay Valley. Fig. 17 shows the longitudinal profile of the Aksay Valley, with geomorphological features marked along its course.

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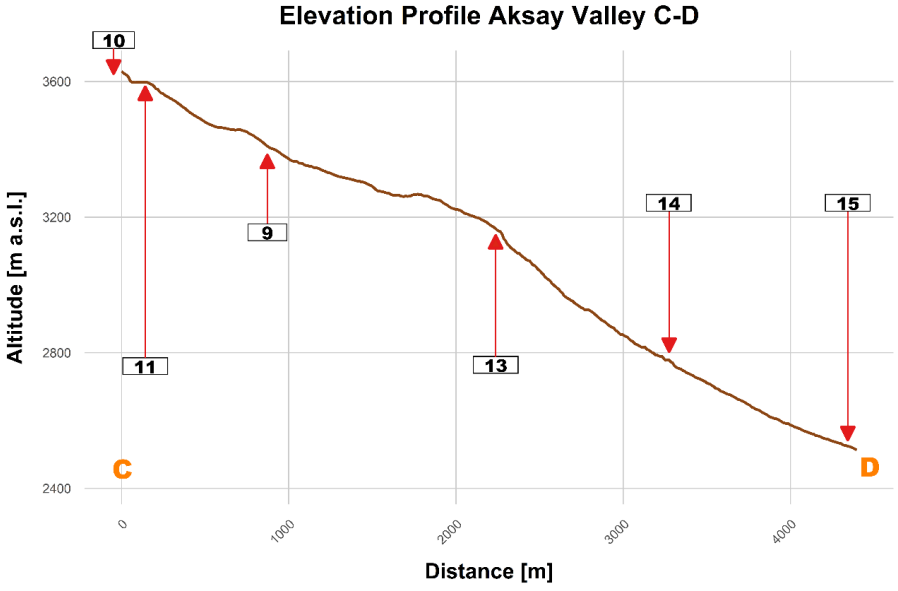

Fig. 17: Longitudinal profile C-D of the Aksay Valley with labeled geomorphological features.

The average slope of the Aksay Valley along the about 4.4 km long section C-D is approximately 14.3 degrees, with an elevation difference of around 1,117 m. Directly adjacent to the Uchitel Glacier and the proglacial lake (geomorph. Features 10 and 11), a roughly 2.2 km long section follows, characterized by a slightly gentler gradient of about 12.4 degrees. This section includes the partially debris-covered terminus of the Aksay Glacier (geomorph. Feature 9) and, in close proximity, its heavily crevassed icefall (geomorph. Feature 12). Beyond this, a steep, partially canyon-like section of the Aksay Valley (geomorph. Features 13-14) extends for approximately 1 km, with an average gradient of nearly 20 degrees and regional slopes of up to 40 degrees. The canyon-like section transitions into a flatter area (average gradient of 12.5 degrees) between approximately 2,800 m and 2,500 m above sea level. This zone contains various moraine deposits on both sides of the Aksay Valley slopes, which have, in some places, led to the formation of kame terraces (geomorph. Feature 15) (Ruiz-Fernandes and Oliva, 2019). The final section of the Aksay Valley (not shown in the longitudinal profile) marks the transition into the less steep main valley of the Ala Archa River. At the mouth of the Aksay Valley lies the largest alluvial fan in the Ala Archa Valley (geomorph. Feature 16), which has diverted the current course of the Ala Archa River westward.

5. Discussion

5.1 Role of Climatic Factors on GLOFs

The results of the station data analysis showed no significant trend in precipitation within the Ala Archa Valley during the study period, and the annual mean precipitation remained approximately constant. This finding is broadly consistent with Zaginaev et al. (2019a), who identified a slight decreasing trend in precipitation in the Ala Archa Valley between 1979 and 2013. Studies by Sorg et al. (2012), Haag et al. (2019) and Wang et al. (2024) highlight the challenges associated with the inherent variability of precipitation as a climatic variable and the difficulty of predicting its future behavior. A significant increase in precipitation may have been a driver for the formation and growth of numerous proglacial lakes in the Ala Archa Valley. However, no significant increase in precipitation was observed, suggesting that its role as a

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long-term climatic factor in influencing GLOF occurrence is minimal. Nevertheless, it is essential to highlight the role of extreme precipitation events as a trigger for GLOFs in the context of precipitation. For example, Erokhin et al. (2018) demonstrated that the 2012 outburst of the periodically water-filled Teztor Glacial Lake was caused by a rapid increase in air temperature and, critically, extreme precipitation.

The station data analysis clearly indicates a significant increase in the annual average temperature in the Ala Archa Valley between 1980 and 2019, with a warming rate of approximately 0.25 °C per decade. The observed warming rate at the Alplager Station exceeds the global warming trend of 0.18 °C per decade recorded between 1973 and 2022 (Samset et al., 2023). This trend closely aligns with findings from other studies on temperature changes across Central Asia. Observed warming in the Tian Shan Mountains ranges between 0.1 °C and 0.2 °C per decade from 1960 to 2007 (Barandun et al., 2020). However, Wang et al. (2024) and Chen et al. (2024) report even higher warming rates of 0.33 °C and 0.34 °C per decade, respectively, for a similar period. The results are also in good agreement with Haag et al. (2019), who reported a warming trend of 0.28 °C per decade across Central Asia between 1950 and 2016. Their analysis of annual and seasonal temperature anomalies further revealed a marked intensification of warming since the mid-1990s. Similarly, Kattel et al. (2020) identified an increasing temperature trend of 0.25 °C per decade across the Kyrgyz Republic between 1960 and 2010, with a substantially stronger warming rate of 0.70 °C per decade between 1990 and 2010 compared to 0.12 °C per decade during 1960-1989. This acceleration is also reflected in the Ala Archa Valley, where warming intensified from the early 2000s onwards (Fig. 4). The weaker warming observed at the Alplager Station during the ablation period compared to the annual temperature trend is consistent with findings from Haag et al. (2019), Wang et al. (2024), Sorg et al. (2012), and Barandun et al. (2020), all of whom reported the strongest warming trends primarily during winter months. However, Barandun et al. (2020) and Sorg et al. (2012) highlight that climate change has significantly extended the ablation period, leading to increased glacier mass loss and accelerated melt. Temperature development is a significant climatic factor for the risk of GLOFs, as it directly influences glacier dynamics, though with a certain time lag.

Both the glaciological analysis of the Golubin Glacier and remote sensing data reveal substantial glacier retreat in the Ala Archa Valley. Comparing the evolution of the Golubin Glacier with the glaciers in the Adygene and Aksay valleys highlights distinct differences in glacier retreat patterns. Between 1964 and 2021, the Aksay Glacier decreased from 4.8 km² to 4.357 km² (-9.3%), the Uchitel Glacier from 2.2 km² to 1.796 km² (-18.4%), and the Adygene Glacier from 3.5 km² to 2.846 km² (-18.7%) (Bolch, 2015; Zholdoshbekov et al., 2023). In contrast, the Golubin Glacier experienced a more moderate reduction from 5.6 km² to 5.138 km² (-8.2%) over the same period (Bolch, 2015; Zholdoshbekov et al., 2023). A similar pattern is evident in glacier mass balance, with higher mass losses observed for the Aksay (-0.52 ± 0.46 m w.e. yr^{-1}) and Uchitel glaciers (-0.44 ± 0.38 m w.e. yr^{-1}) between 1964 and 2012 (Bolch, 2015). The Adygene Glacier exhibited the strongest mass loss among glaciers larger than 0.5 km² in the Ala Archa Valley, with a geodetic mass balance of -0.66 ± 0.38 m w.e. yr^{-1} between 1964 and 2012 (Bolch, 2015). In comparison, the Golubin Glacier showed a lower average mass balance of -0.314 to -0.353 m w.e. yr^{-1} between 1969 and 2024. Although the mass-balance estimates for Aksay and Adygene are based on geodetic methods and therefore contain greater uncertainties than the Golubin record, these differences demonstrate substantial spatial variability in glacier response within the Ala Archa Valley. These differences are primarily related to glacier-specific characteristics. The smaller, highly fragmented Uchitel and Adygene glaciers, with their limited accumulation zones, are particularly sensitive to climatic fluctuations and therefore experience greater mass and area loss than the larger glaciers in the region (Sorg et al., 2012; Bolch, 2015). In contrast, the larger Golubin and Aksay glaciers show greater resilience to warming, with the Aksay Glacier benefiting from debris cover at its terminus and its shaded position along the valley walls, both of which reduce melt rates (Zaginaev et al., 2019a). Nevertheless, the glaciological observations of the Golubin

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Glacier indicate a marked acceleration in mass loss since the 2000s, characterized by record-negative mass-balance values.

The glacier retreat observed in the Ala Archa Valley aligns closely with trends across the Tien Shan Mountains, where glacierized area declined by approximately 18% between 1961 and 2012 (Farinotti et al., 2015). However, glacier response within the Tien Shan is highly heterogeneous, with lower mass losses in the central Tien Shan and stronger retreat in the eastern and western margins of the range (Sorg et al., 2012; Barandun et al., 2021). For glaciers in the western Tien Shan, Barandun et al. (2021) calculated a geodetic mass balance of -0.30 ± 0.37 m w.e. yr^{-1} between 1999 and 2018, compared to -0.35 ± 0.85 m w.e. yr^{-1}, -0.60 ± 0.59 m w.e. yr^{-1}, and -0.65 ± 0.65 m w.e. yr^{-1} for the Aksay, Uchitel, and Adygene glaciers, respectively, between 1999 and 2012 (Bolch, 2015). Compared to the European Alps, glacier mass loss in the Ala Archa Valley is less pronounced, with Alpine glaciers showing an average geodetic mass balance of -0.712 ± 0.143 m w.e. yr^{-1} between 2000 and 2012 (Sommer et al., 2020). Nevertheless, glacier retreat in the Tien Shan remains approximately four times higher than the global average (Farinotti et al., 2015).

Climate change has driven a significant temperature increase in the Ala Archa Valley, triggering pronounced glacier retreat and initiating the formation of numerous glacial lakes. However, unlike the global trend reported by Zhang et al. (2025), this warming has not led to a drastic rise in GLOF events. The analysis of the GLOF database for the Ala Archa Valley revealed a significant decline in GLOF occurrences in the Ala Archa Valley despite ongoing climate change. This decline occurred primarily in the period from the 1960s to the 1970s when global warming and glacier melting began to accelerate. Therefore, these findings suggest that additional factors beyond temperature and glacier mass loss are critical in determining GLOF occurrence.

A closer examination of historical GLOF events in the Ala Archa Valley reveals that they are primarily concentrated in the Aksay Valley. Aside from the 11 GLOFs originating from the Teztor tributary valley, no GLOF has been documented in the Adygene Valley. This is remarkable given that glacier melt in the Adygene Valley was the most pronounced in the study period, with the Adygene Glacier exhibiting melt rates comparable to many Alpine glaciers. Despite the formation of a cascade of proglacial lakes due to glacier retreat, no GLOF has been recorded from these lakes. Thus, climatic factors alone cannot explain the overall trend of GLOFs in the Ala Archa Valley and their spatial bias toward the Aksay Valley. The trend of GLOF occurrences in the Ala Archa Valley hence contradicts the pattern of climatic warming. Therefore, geological and, particularly, geomorphological factors must be considered in explaining the spatial and temporal variations in GLOF occurrences.

5.2 Role of Local Geomorphological Factors on GLOFs

Before comparing the geomorphological characteristics of the Adygene and Aksay valleys, it is necessary to assess whether differences in geology could explain the contrasting GLOF activity. Both catchments are situated within the same Caledonian Fold Zone and share a comparable tectonic framework. Although the region is seismically active and located close to the Chonkurchak Fault (Zaginaev et al., 2019a), both valleys are expected to experience a similar probability of earthquake-triggered GLOFs. Likewise, lithological differences are limited, as both catchments are dominated by Paleozoic granitoid rocks (Zaginaev et al., 2019a). Although granites, granodiorites, and diorites differ slightly in their resistance to weathering, such variations are unlikely to explain the pronounced differences in GLOF occurrence. While petrographic variations between the valleys are not significant, they may still influence slope stability and, thus, the geomorphology of the valleys.

As previously mentioned, the two valleys have similarly sized catchment areas but differ significantly in their gradients. The Aksay Valley has a considerably steeper average slope than the Adygene Valley, particularly in its canyon-like section. In their GLOF simulations,

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Meyrat et al. (2024) identified this section as an area of intense erosional processes and a key sediment source due to its steep gradient and abundance of easily erodible material. In contrast, the Adygene Valley lacks such an extremely steep section and is characterized by gentle U-shaped glacial troughs in its lower section, which are absent in the Aksay catchment. In addition to the overall slope differences, the two valleys also differ in their longitudinal profiles. The Aksay Valley has a largely undisturbed profile with few significant knickpoints, while the longitudinal profile of the Adygene Valley is much more irregular. However, the comparison of valley morphology alone only partially explains the contrasting GLOF activity in the Ala Archa Valley. In the Aksay Valley, steep gradients, large volumes of loose material, and easily erodible kame terraces facilitate sediment mobilisation. As a result, a glacial lake outburst there can rapidly develop into a debris or mudflow further downstream, significantly increasing its spatial impact and destructive potential (Meyrat et al., 2024). Thus, valley morphology influences GLOF dynamics and intensity rather than the initial occurrence of outbursts. Far more decisive for the actual outburst risk, however, are the specific geomorphological characteristics in each valley, which will be discussed in detail in the following section.

The Ala Archa Valley hosts several active rock glaciers, which are considered indicators of permafrost in the Tien Shan Mountains and often border smaller polythermal glaciers. The two largest rock glaciers in the Adygene catchment are directly adjacent to the Teztor and Adygene glaciers (Erokhin et al., 2018). In contrast, such rock glaciers are entirely absent at the termini of the Aksay and Uchitel glaciers, as demonstrated by Zaginaev et al. (2019a) and Ruiz-Fernandes and Oliva (2019). Zaginaev et al. (2019b) identified the regionally variable occurrence of rock glaciers as one of the primary drivers of small-scale variations in GLOF activity. They showed that the occurrence of GLOFs is closely related to the ratio of moraine area to glacier area (M/G Ratio) rather than glacier retreat. A lower M/G Ratio, such as 0.34 in the Aksay Valley, indicates a greater proportion of debris-free glacier area relative to the moraine area, which the authors associate with increased GLOF and debris flow activity. In contrast, a higher ratio, such as 0.56 in the Adygene Valley, has a stabilizing effect and decreases the frequency of such events. Zaginaev et al. (2019b) attribute this to the stabilizing role of moraine complexes and rock glaciers, which regulate meltwater runoff, limit sediment mobilization and erosion, and thereby reduce debris-flow activity. In some cases, rock glaciers themselves function as dams for glacial lakes, as shown by Blöthe et al. (2018), which partially applies to the numerous thermokarst lakes in the Adygene Valley. However, due to their limited storage capacity for liquid water (Jones et al., 2019), rock glaciers can only moderate or delay flood waves rather than prevent GLOFs. The argumentation of Zaginaev et al. (2019b) can therefore be partially accepted, as the rock glacier has a significant influence on debris flow activity but, similar to the different valley morphology, is not primarily responsible for the occurrence of GLOFs. Rather, like valley morphology, the rock glacier influences the dynamics and intensity of post-outburst consequences. This underscores the need for a detailed analysis of the glacial lakes within the two valleys themselves.

The type of glacial lake and its specific characteristics result in different levels of outburst risk for the glacial lakes in the Adygene and Aksay valleys. For the proglacial lakes in the Adygene Valley, it is evident that the lake with the largest volume does not necessarily have the highest outburst risk. According to the findings of Falatkova et al. (2019), the Large Adygene Lake, one of the three proglacial lakes of the Adygene Glacier has the lowest outburst risk. Since the dam of this lake consists largely of stable bedrock and drainage occurs primarily through surface channels, the lake's water level is effectively regulated, limiting further lake expansion. As a result, the likelihood of a glacial lake outburst is low. In contrast, the Lower Adygene Lake and the Upper Adygene Lake exhibit a much higher outburst risk. Both lakes feature subsurface drainage behavior typical of moraine-dammed glacial lakes, which increases outburst risk due to the potential blockage of underground drainage channels. Additionally, their dams partially consist of dead ice and ice lenses, which could destabilize and ultimately breach the dam if melted. For the Lower Adygene Lake, there is an additional risk of landslides

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or rockfalls triggering an outburst. Sudden overflow or outburst from upstream glacial lakes could also act as a trigger. The Upper Adygene Lake faces another risk factor: its direct contact with the glacier. This makes the lake highly dependent on the glacier's dynamics, as it is continuously fed by meltwater, which can rapidly raise the lake's water level and lead to an outburst. Overall, Falatkova et al. (2019) classify the outburst risk for the Lower and Upper Adygene Lakes as moderate. As for the numerous thermokarst lakes on the rock glacier in the Adygene Valley, their small size and episodic or periodic water levels mean they pose no significant outburst threat.

The Uchitel Glacial Lake in the Aksay Valley shares nearly identical geomorphological and hydrological characteristics with the Upper and Lower Adygene Lakes. The lake has recently developed subsurface drainage and exhibits highly fluctuating water levels despite having a comparatively smaller volume than the glacial lakes in the Adygene Valley. Additionally, ice lenses are embedded within its dam structure, and similar to the Upper Adygene Lake, it is directly fed by meltwater from the adjacent glacier. Due to these factors, Zaginaev et al. (2019a) classify the Uchitel Glacial Lake as potentially at risk of outburst. The glacial lakes in the Adygene and Aksay valleys have very similar characteristics and, with the exception of the Large Adygene Lake, a comparably high risk of outburst. However, no GLOF has been recorded from the cascade of proglacial lakes in the Adygene Valley. Thus, the hydrological and geomorphological characteristics of the lakes do not sufficiently explain the regionally unbalanced occurrence of GLOFs in the Ala Archa Valley. Attention should therefore be directed toward another geomorphological feature in these two valleys: the glaciers themselves and their partially distinct geomorphology.

As shown in Chapter 4.5, the termini of the Adygene and Uchitel glaciers are very different. While the Adygene Glacier has a very flat, partially debris-covered terminus and loses mass primarily through ablation, the terminus of the Uchitel Glacier consists of ice cliffs 15 to 25 meters high. Therefore, the Uchitel Glacier loses mass not only by ablation but also by calving into the adjacent glacial lake. This makes calving a critical trigger for a glacial lake outburst at the Uchitel Glacial Lake, as the collapse of large ice cliffs can generate flood waves capable of overtopping the dam and triggering an outburst. Zhang et al. (2023) identify glacier calving as one of the major global triggers of glacial lake outburst, along with ice avalanches. Such a trigger is absent in the Adygene Valley. Although the Upper Adygene Lake is directly adjacent to the glacier, the glacier does not calve into the lake.

Meyrat et al. (2024) identify the Uchitel Glacial Lake as the primary source of GLOF events in the Aksay Valley. The most recent outburst of this lake occurred in 2015, causing damage to downstream tourist infrastructure (Niggli et al., 2026). However, the Uchitel Glacial Lake is not the only potential source of GLOFs in the Aksay Valley. As identified through the analysis of the GLOF database, several GLOF events recorded in the Aksay Valley have been attributed to the outburst of englacial water pockets. This glacial lake type is the most challenging to observe and occurs relatively infrequently. According to studies by Zaginaev et al. (2016) and Zaginaev et al. (2019b), all documented GLOFs of this type in the Ala Archa Valley originated from englacial water pockets within the Aksay Glacier. As demonstrated in Chapter 4.5, the Aksay Glacier features a pronounced icefall in its ablation zone, which is closely linked to the outburst of these englacial water pockets (Zaginaev et al., 2019a). Particularly during the 1960s and 1980s, numerous GLOFs occurred in the Aksay Valley, triggered by englacial water pockets within the Aksay Glacier. These outbursts led to a peak in GLOF activity in the Ala Archa Valley (Zaginaev et al., 2019a). Notably, these outbursts occurred during a period when the Aksay Glacier exhibited no retreat and even temporarily showed a slightly positive mass balance. In areas of intense ice deformation, such as typical icefall zones, deep crevasses allow meltwater to infiltrate the glacier, forming extensive englacial drainage systems (Fountain and Scott Walder, 1998). However, these crevasses simultaneously disrupt the englacial drainage system, particularly during minor glacier advances with increased ice velocity, which destabilize and partially destroy existing drainage pathways. In the icefall zone of the Aksay Glacier, the minor glacier advance during the 1960s locally blocked englacial

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meltwater channels. This led to the accumulation of englacial water pockets, which abruptly burst upon reaching critical hydrostatic pressure (Zaginaev et al., 2019b). The repeated outbursts from the Aksay Glacier resulted in the formation of the distinctive alluvial fan of the Aksay River (Niggli et al., 2026). After the period of increased GLOF activity in the Aksay Valley, the Aksay Glacier experienced a strong glacier retreat, a trend that continues to the present day. As a result of intense glacier melt, the velocity of glacier ice subsequently decreased, leading to the stagnation of the glacier tongue, which reduced the probability of a blockage of the englacial meltwater channels (Zaginaev et al., 2019b). Correspondingly, the number of documented GLOFs in the Aksay Valley declined sharply. This demonstrates that the increased GLOF activity during the 1960s and 1980s in the Aksay Valley was not driven by enhanced glacier melt but rather by the glacier's specific geomorphology and internal structure, particularly its pronounced icefall. In contrast, the glacier in the Adygene Valley has a fundamentally different structure: it lacks extensive crevasses or a distinct icefall, thereby providing no comparable conditions for the formation of englacial water pockets that could trigger outbursts.

5.3 Comparison with Regional and Global GLOF Trends

In contrast to numerous previous studies, the findings of this study suggest a different perspective on climate change's impact on GLOFs. For instance, Kattel et al. (2020), Chen et al. (2024), and Zheng et al. (2021) attribute the rising GLOF risk in the Kyrgyz Mountains, the Tien Shan, and the broader HMA region, respectively, to climate change, highlighting the significant increase in both the number and surface area of glacial lakes. According to Chen et al. (2024), this risk will increase further if global warming accelerates in the future. The findings of Wang et al. (2024) and Zhang et al. (2023) go a step further, as they not only identified an increasing GLOF risk for the HMA region and, in the case of Zhang et al. (2025), on a global scale, but also documented a significant rise in actual GLOFs driven by climate change. According to Zhang et al. (2023, 2025), the HMA region has experienced a pronounced rise in GLOF frequency since the 1980s. Similarly, Zhang et al. (2024) observed a global increase in GLOFs starting in 2000. These trends strongly contrast with the marked decline in GLOF events observed in the Ala Archa Valley since the 1960s. However, Zhang et al. (2024) emphasize that an increase in moraine- and bedrock-dammed lakes does not necessarily lead to a higher GLOF risk. This aligns with findings in this study, where the presence of proglacial lakes, such as the cascade of glacial lakes in the Adygene Valley, has not resulted in outbursts to date.

However, several other studies also conclude that geomorphological factors play a significant role in the evolution of glacial lakes and are largely responsible for their outbursts. For example, Daiyrov et al. (2022) argue that climatic factors are far less significant than local geomorphological conditions in driving seasonal volume fluctuations of glacial lakes. The work of Zaginaev et al. (2019b) highlights, as previously outlined in the context of the Moraine/Glacier ratio, that geomorphological factors have a greater influence on GLOF occurrence than climatic variables such as glacier retreat. Carrivick and Tweed (2016) observed a general decline in GLOF events in some regions since the mid-1990s, attributing this trend primarily to reduced outbursts from ice-dammed lakes. Veh et al. (2023) confirmed this pattern, highlighting in their study a significant decrease in the intensity of outbursts from ice-dammed lakes since 1900. Additionally, a slight decrease in such GLOFs has been observed across the HMA region since the 1960s. Because only outbursts from moraine-dammed lakes and englacial water pockets have been documented in the Ala Archa Valley, the findings of Harrison et al. (2018) are particularly relevant for interpreting the results of this study. They documented a surge in global outbursts from moraine-dammed lakes between 1930 and 1970, which was followed by a decline after 1975, a trend comparable to that in the Ala Archa Valley. Veh et al. (2022) came to similar conclusions, identifying the year 1973 as a turning point in GLOF frequency. While the annual GLOF rate increased significantly worldwide from 1900 to 1973, they recorded a 25% decline in the annual GLOF rate between

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1973 and 2017. This contrasts distinctly with the observed accelerated temperature rise since the mid-1970s. On a regional scale, Veh et al. (2022) detected no substantial trend in GLOF occurrence and additionally found no significant correlation between temperature trends and GLOF frequency in the HMA region from 1973 to 2017. These results are in line with the findings of this study, which found no credible evidence of a correlation between the outburst of glacial lakes and changes in temperature. However, Veh et al. (2022) point out that the actual documented number of GLOFs may be biased. They argue that due to increased scientific interest in glaciers and advancements in methods such as remote sensing, the actual number of GLOFs in the early 20th century may have been significantly higher than documented. This perspective is further supported by Zhang et al. (2025), who identified an increasing GLOF trend in HMA since 1980 after accounting for previously undocumented events. Similarly, in the Ala Archa Valley, Zaginaev et al. (2016) retrospectively identified numerous GLOF events through dendrochronological analyses that were previously undocumented.

The decline in recorded moraine-dammed GLOFs in the Ala Archa Valley could be explained by the hypothesis proposed by Harrison et al. (2018). They argue that there is a response time of about 45 to 200 years between a climatic change and the eventual outburst of a glacial lake. Specifically, they divide this response period into three phases. After a climatic change, glaciers first undergo an adaptation phase in which they respond to the new climatic conditions. Next, glacial lakes begin to form, and their development and expansion require a certain amount of time, known as the limnological response time. The final outburst of these lakes can only occur after this phase together with an additional time lag. For this reason, Harrison et al. (2018) interpret the increased GLOF activity between 1930 and 1970 as a delayed consequence of the warming that marked the end of the Little Ice Age. This increased GLOF activity is clearly evident in the Ala Archa Valley during the 1960s and 1970s. Furthermore, the hypothesis proposed by Harrison et al. (2018) may also provide an explanation for why, despite the high number of glacial lakes in the Adygene Valley, no documented glacial lake outburst has occurred to date. As a result of anthropogenic forced climate change, the Adygene Valley experienced significant glacier retreat after a certain response time, which, with a temporal lag, subsequently favored the formation of the cascade of proglacial lakes. These lakes are still developing, and as they continue to grow, the risk of outburst could increase significantly. Therefore, it is possible that the full impacts of climate change, particularly in the form of another increase in GLOFs, will only become evident in the Ala Archa Valley after a substantial delay of years or even decades. For this reason, a monitoring station was established at the Large Adygene Lake in 2008, as the risk of an outburst is expected to increase with the continued retreat of the Adygene Glacier and the potential further growth of the lake (Falatkova et al., 2019). The increase in GLOF events documented in this study, from one in the 2000s to two in the 2010s, may already indicate a gradual rise in GLOF activity in the Ala Archa Valley.

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6. Conclusions

This study investigates the influence of climatic and geomorphological factors on GLOF occurrence in the Ala Archa Valley, Northern Tien Shan Mountains. The valley was selected as the study area due to the availability of well-documented glaciological and climatological data, as well as detailed records of past GLOFs. Specifically, the Adygene Valley and the Aksay Valley, two tributary valleys of the Ala Archa Valley, were selected as the study area as they demonstrate clear differences in GLOF occurrence and differ significantly in their geomorphological characteristics.

Using meteorological, glaciological, and remote sensing data, the climatic drivers of GLOF occurrence were analyzed. The results revealed a pronounced temperature increase and substantial glacier retreat, while precipitation remained largely unchanged. Glacier retreat has facilitated the formation of numerous new proglacial lakes, particularly in the Adygene Valley. However, despite these climate-induced changes, documented GLOF events in the Ala Archa Valley have declined significantly since the 1960s and are spatially concentrated in the Aksay Valley. Thus, climatic factors alone cannot explain either the temporal evolution or the spatial distribution of GLOFs in the study area.

Therefore, the geological and tectonic conditions, as well as geomorphological factors, were analyzed in detail. While the geological and tectonic settings of both valleys were comparable, substantial geomorphological differences were identified. The analysis showed that differences in valley morphology and the presence of rock glaciers in the Adygene Valley could not directly explain the asymmetric occurrence of GLOFs in the Aksay Valley, as these factors primarily influence the further downstream evolution of an occurred GLOF. In contrast, comparing the glacial lake properties yielded more insights. It was found that some glacial lakes in the Adygene Valley pose a low outburst risk, whereas the Uchitel Glacial Lake exhibits a significantly higher risk, particularly due to the glacier calving directly into the lake. However, the key factor explaining the regional disparity in GLOF occurrence within the Ala Archa Valley was the different geomorphology of the glaciers in the two valleys. The frequent outbursts of englacial water pockets in the 1960s and 1970s were linked to the unique internal structure of the Aksay Glacier, its pronounced icefall, and a minor glacier advance. The Adygene Glacier entirely lacks these features, which explains the absence of significant GLOF events.

However climatic factors have established preparatory conditions for future GLOFs in the Ala Archa Valley, particularly in the Adygene Valley. The observed decline in GLOF frequency in the study area could be attributed to a delayed response of glaciers and glacial lakes to climate changes following the end of the Little Ice Age. The full impacts of climate change, particularly in the form of a renewed increase in GLOFs in the Ala Archa Valley, may therefore only become evident after a significant delay. Nevertheless, research into the complex interactions between climate change and multifactorial natural hazards such as GLOFs remains in its infancy (Harrison et al., 2018). Further studies are therefore urgently needed to refine predictive models and better assess the risks posed by future GLOFs.

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Data availability

A detailed description of all data sources and processing steps is provided in Sect. 3. In summary: meteorological data from the Alplager Weather Station were provided by Azisov et al. (2022) and are not publicly available due to institutional data policies; they can be obtained from the corresponding author upon reasonable request. Glaciological data from the Golubin Glacier are publicly available from the WGMS (2026) at https://wgms.ch. Reconstructed mass balance data were provided by Azisov et al. (2022). Corona satellite imagery and glacier outlines for 1964 were provided by Bolch (2015). Glacier outlines for 2021 were provided by Zholdoshbekov et al. (2023). PlanetScope satellite imagery (2024) was obtained from Planet Labs (https://www.planet.com/explorer/) and is subject to Planet Labs' terms of use. The High Mountain Asia 8 m digital elevation model was obtained from Shean (2017). The GLOF database (HMAGLOFDB v1.3.0) is available from Steiner and Shrestha (2026). All other data are available from the corresponding author upon reasonable request.

Code availability

The R scripts used for statistical analyses and visualization of meteorological and glaciological data are available from the corresponding author upon reasonable request. QGIS was used for GIS analyses and map production; no custom code was developed for these tasks.

Author contributions

F.H. designed the study, chose the methodology, performed the data analysis, and wrote the original draft. O.B. contributed to supervision and reviewed and edited the manuscript. B.M. provided local expertise, facilitated access to data and field sites through CAIAG, and contributed to data curation and resources. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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