Constantly renewing glacial lakes in the Kyrgyz Range, northern Tien Shan

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Abstract. In the Kyrgyz Range of the northern Tien Shan, Central Asia, glacial lakes have been a focus of monitoring because of due to the increasing concern over glacial lake outburst floods (GLOFs) amid notable glacier recession. This study investigates (1) the historical evolution in the numbers and area of glacial lakes (each>0.00045 km²) for the period 1968, 2000, and 2021, using Corona KH-4, Landsat 7, and Sentinel-2 imagery, and (2) the relationship between lake development and the evolution of glacier-moraine complexes (GMCs) containing buried ice. The number of glacial lakes doubled between 1968 and 2021, while the total area increased by 76% (0.80 to 1.42 km²). However, 190 out of 274 lakes present in 1968 had disappeared by 2000. Many new lakes had emerged by 2021, with one lake reappearing after a prior disappearance since 1968. Rapid lake formation was associated with a 3231% reduction in glacier area over the past 50 years and the evolution of GMCs. The expansion and melting of buried ice withinof IDCs GMCs led to new surface depressions (thermokarst features) and subsequent lake formation, resulting in continuous glacial lake renewal. Thus, the continuous renewal of glacial lakes in the Kyrgyz Range results from the combined effects of glacier retreat, GMC expansion, and buried ice melt.

1 Introduction

It has been reported that the number of glacial lakes in high high-mountain regions of Asia is rapidly increasing (Zhang et al., 2023). In the Kyrgyz Range, located in the northern Tien Shan of the Kyrgyz Republic, hundreds of glacial lakes have beenare identified by satellite data (Kattel et al., 2020; Daiyrov et al., 2022). Development of these lakes predominantly occurs on glacier glacier-moraine complexes (GMCs, Shatravin, 2007; Erokhin, 2011), which formed during glacier retreat after the Little Ice Age (LIA). GMCs, is also referred to as the ice-debris complexes (Bolch et al., 2018; Blöthe et al., 2021), are. A GMC is a geomorphological units that composedbined of buried ice andwith debrismoraine deposits, and are withoutcharacterized by the absence of clear distinct moraine ridges. Post-Little Ice AgeIA climatic warming has induced geomorphological transformations ofin the recessional zones of glacier termini, where these moraine deposits, with glacier buried ice has become becoming isolatedtrapped beneathunder debris as buried ice during glacier recession (Maksimov, 1982; Maksimov and Osmonov, 1995; Erokhin et al., 2017). As this buried ice has melted, numerous glacial lakes formed on GMCs, sometimes in direct contact with their parent glaciers, but often as independent thermokarst lakes (Janský et al., 2008). Lakes directly connected to glacier terminus termini typically exhibit faster expansion due to glacier recession, though lakes indirectly connected lakes through debris-covered ice can also enlarge through debris-covered ice as that ice melts (Daiyrov et al., 2018; 2022). Approximately 20% of these lakes are considered potentially hazardous (Janský et al., 2008, 2010).

Monitoring glacial lakes in the Kyrgyz Range is critical, as repeated GLOFs have caused severe damage (Erokhin et al., 2008, 2017; Kattel et al., 2020). Systematic research began in the 1960s following catastrophic GLOF events in the Kyrgyz Republic~~stan~~. In the central part of the Kyrgyz Range, at least 22 GLOF events have been recorded since 1952 (Erokhin, 2011; Zaginaev et al., 2016), including recent floods and debris flows such as Takyrtor glacial lake on 5 June 2009, Teztor glacial lake on 31 July 2012, Chelektor glacial lake on 12 August 2017, Akpai glacial lake on 2 August 2021 (Erokhin et al., 2017; Kattel et al., 2020; Daiyrov et al., 2022), and Takyrtor glacial lake on 27 June 2025. These events have damaged infrastructure, agricultural fields, and downstream settlements (Erokhin et al., 2017; Zaginaev et al., 2019), demonstrating the need for ongoing hazard assessment (Kattel et al., 2020; Daiyrov et al., 2022). Compared to the eastern Himalayas, where the glacial lakes have been expanding continuously for decades (Yamada et al., 1998; Komori et al., 2004; Nagai et al., 2017), glacial lakes in the northern Tien Shan, including the Kyrgyz Range, are smaller and more susceptible to unstable, short-term fluctuations due to geomorphological conditions~~,~~ such as drainage through~~of~~ ice tunnels within GMCs (Daiyrov et al., 2018; Narama et al., 2018). Despite often being small, these lakes can pose significant hazards, especially ~~since~~ because ~~these~~ lakes described as "short-lived" (Narama et al., 2010, 2018; Daiyrov et al., 2018, 2022; Daiyrov and Narama, 2021) or "non-stationary" (Erokhin et al., 2017) ~~lakes~~ may form and drain in rapid succession, sometimes producing catastrophic GLOFs.

The increase in glacial lakes has been reported across High Mountain Asia (HMA). However, the processes of glacial lake formation and the factors responsible for ~~behind~~ GLOFs vary greatly from region to region. To accurately understand the relationship between glacial lake development and GLOFs, it is essential to clarify~~understand~~ the distinctive characteristics~~features~~ of each locality. In the Kyrgyz Range, Central Asia, previous studies have documented lake numbers and areas (Shatravin and Stavisski, 1984; Jansky et al., 2006; Usubaliev and Erokhin, 2007; Erokhin, 2008; Falatkova et al., 2019; Daiyrov et al., 2022). Despite these observations, ~~of the number and area of glacial lakes,~~ long-term changes in glacial lakes and the processes driving lake renewal in this region remain insufficiently documented. To understand the characteristics of glacial lake formation history ~~in glacial lakes~~ and to clarify the processes of rapid glacial lake renewal in the Kyrgyz Range, this study investigates (1) the historical evolution in the number~~s~~ and area of glacial lakes during 1968, 2000, and 2021, based on Corona KH-4, Landsat 7/ETM+, and Sentinel-2 imagery, and (2) the relationship between lake development and the evolution of glacier-moraine complexes (GMCs) containing buried ice. The latter relationship ~~was~~ is investigated through analysis of glacier area changes derived~~due to~~ from mu~~a~~ulti~~various~~ remote sensing datasets~~imagery~~ and ~~d~~ digital elevation models (DEMs) ~~for the study~~.

2 Study area

The study area is the Kyrgyz Range in the northern Tien Shan (Fig. 1), where~~with~~ mountain ridges rang~~e~~ing from 2,500 to 4,900 m above sea level. The ~~central~~ northern flank of the central part, which contains~~has~~ many glaciers, is higher than the eastern and western ~~flanks~~parts. Post-glacier~~-~~-retreat GMCs consisting of ~~dead~~buried ice and debris are widely distributed at glacier fronts (Shatravin, 2007). These GMCs are distinct from debris-covered glaciers. ~~, and the l~~Lakes forming on ~~them~~

GMCs are typically small, thermokarst-type, and, non-stationary, and thermokarst type, although some are connected by internal drainage channels, leading to GLOFs (Narama et al., 2018). Some GMC termini have evolved into glacier-derived rock glaciers. Climate change over recent decades has driven glacier and GMC shrinkage and degradation of both glaciers and GMCs (Erokhin et al., 2017; Daiyrov et al., 2022).

InOn the northern flank of the central part of the Kyrgyz Range, total, 483 glaciers covering approximately 520 km² between 3,100 and 4,200 m elevation have been identified (Usubaliev et al., 2013), mainly concentrated mostly in the central river basins including Issyk-Ata, Alamudun, West-Karakol, and Sokuluk river basins (Maksimov and Osmonov, 1995; Usubaliev et al., 2013). In the The Ala-Archa basin, glacier area decreased by 15.2–18% between 1963/64 and 2003–2010 (Aizen et al., 2006; Bolch, 2015). The Golubin Glacier (5.42 km²) is the largest in the Kyrgyz Range, and has with a long-term mass balance of averaging −0.20 ± 0.42 m w.e. yr^{-1}/year from 1949/50 to 2020/21 (Azisov et al., 2022). The largest GMC (~3 km²) is located at the Ken-Tor glacier front in the Noruz River river basin (Figs.1 and 6, Maksimov and Osmonov, 1995). Precipitation peaks between March and July, with an average annual precipitation of 787 mm and a mean annual temperature of −3.5°C (1969-2005) at the Teo-Ashuu meteorological station (3,400 m) in the central part of the range. Precipitation is a critical factor contrallingcontrollinginfluencing glacier mass balance in this region (Ponomarenko, 1976; Aizen et al., 2006).

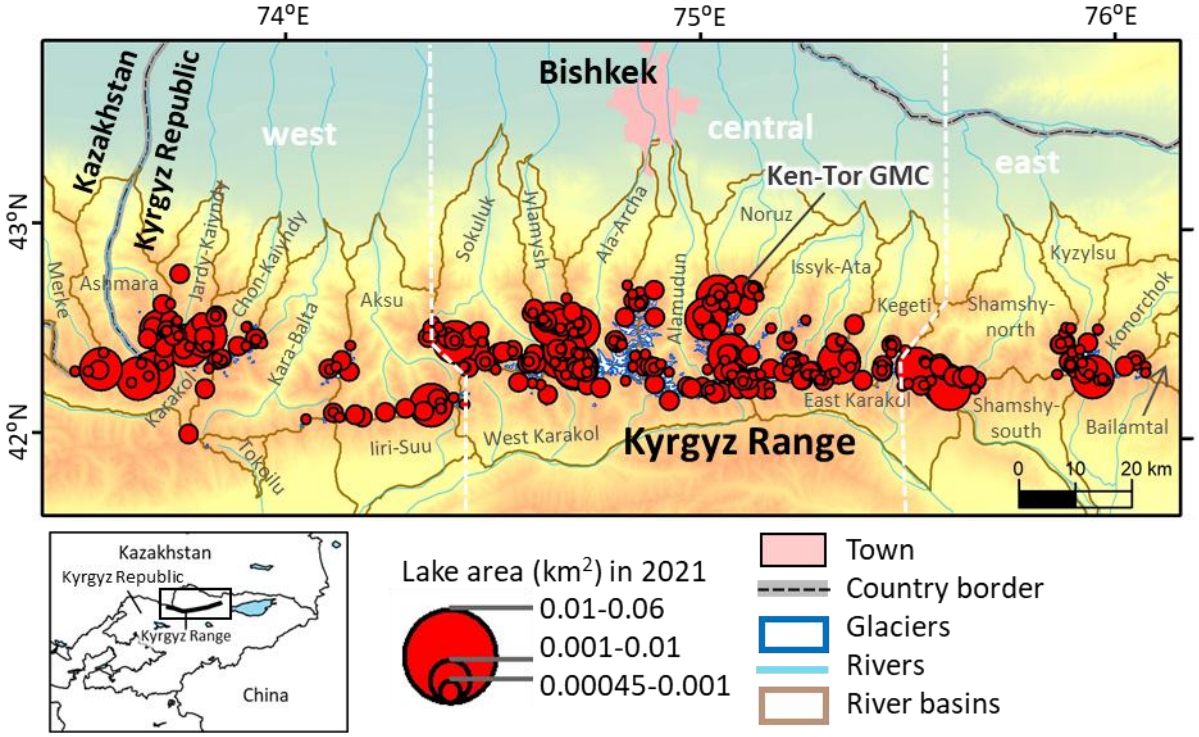

Figure 1: Maps of the study area in the Kyrgyz Range, northern Tien Shan. The top map shows the Kyrgyz Range, with glacial lakes in 2021 marked by red circles. The bottom left map highlights study sites in Kyrgyzstan. The Kyrgyz Range is divided into three sections by white dotted lines. Glacial lake sizes correspond to circle diameters.

3 Methods

3.1 Satellite data collection

To quantify ~~the~~ historical changes in glacial lakes and glaciers ~~with~~in the Kyrgyz Range, we u~~tilize~~se~~tilize~~d a combination of satellite remote sensing datasets spanning five decades using Corona, Landsat 7/ETM+ and Sentinel-2. Thirteen ~~near~~ near-cloud-free Corona KH-4 stereo photographs from 1964 and 1968 ~~formed provided~~provide the earliest dataset, covering 2% (~~predominantly~~ mainly 14 glaciers on the eastern part) and 98% of the study region, respectively. Each image ~~spans~~ covers about~~~~ 16 km in width, with a spatial resolution between 1.8 and 2.7 m~~eters~~ (Table 1). DEMs and orthoimages were generated from forward and aft stereo ~~image~~ pairs using Metashape (Agisoft), and~~with~~ geometric distortions were corrected using~~via~~ a non-metric camera model. Ground control points (GCPs) for geometric correction were systematically selected~~chosen~~ from stable terrain features, such as large boulders, outside glacier and GMC areas. Coordinates were taken~~derived~~ from QuickBird images in Google Earth~~'s QuickBird images~~ and advanced land observing satellite/panchromatic remote sensing instrument for stereo mapping (ALOS/PRISM) ortho-images (2.5 m resolution) acquired in~~dated~~ 2007, while vertical references were based~~originated~~ on the ~~from~~ high mountain Asia (HMA) DEM ~~data~~ (8 m resolution) from 2017. Each ~~each~~ stereo pair, ~~processing employed~~ 25–30 GCPs were used and grouped into ~~segmented into~~ four sub-area~~s groups~~ (a–d), and ~~carefully excluding~~ cloudy or snow-covered features were excluded~~to~~ to ensure~~preserve~~ accuracy. The final Corona-derived DEM and orthophotos have spatial resolutions of~~achieved~~ 4.1 m and 2.0 m ~~spatial resolutions~~, respectively. We also used orthoimages from~~of~~ Landsat 7/ETM+ acquired in 2000 (15 m) and Sentinel-2 ~~(10 m)~~ in 2021 (10 m; Table 2). ~~We used~~ Landsat 7 pan-sharpened images were generated~~converted~~ from 15 m panchromatic (~~8~~ band 8) and 30 m multispectral bands~~images~~ using ArcGIS Pro. Only~~These~~ scenes with~~out~~ minimal~~significant~~ cloud or snow coverage ~~contamination~~ were selected~~used~~ ~~from analysis~~ to maintain data quality and reliability.

Table 1: List of Corona KH-4 images of the study area.

Satellite	Corona Scenes	Date	Ground resolution (m)	Coverage area in study area (%)
KH-4A 10 (Corona 85, Mission 1010, OPS 3497)	DS1010-2086DA121	20.09.1964	2.7	east part : 2%
	DS1010-2086DA120			
	DS1010-2086DF114			
	DS1010-2086DF115			
KH-4A 48 (Corona 128, Mission 1048, OPS 0165)	DS1048-1039DA030	18.09.1968	2.7-7.6	west, central and east part: 74%
	DS1048-1039DA031			
	DS1048-1039DA032			
	DS1048-1039DF030			
	DS1048-1039DF031			
	DS1048-1039DF032			
KH-4B 4 (Corona 127, Mission 1104, OPS 5955)	DS1104-2185DF053	07.08.1968	1.8	central-south and east part: 24%
	DS1104-2185DA057			
	DS1104-2185DA058			

3.2 Mapping of glacial lakes, glaciers, and GMCs

To assess~~understand the~~ changes in the ~~of the~~ area~~s~~ and number~~s~~ of glacial lakes in the Kyrgyz Range since 1960s, we manually digitized ~~glacial~~ lakes from Corona KH-4 images (1964, 1968), Landsat 7/ETM+ (2000), and Sentinel-2 (2021) using ArcGIS Pro (Table 2). Manual mapping provides~~ensures~~ higher delineation accuracy than ~~compared to~~ semi-automated methods, although boundary uncertainties remain~~persist~~ at pixel-scale~~level~~ interfaces between water and land. Unclear ~~outline of~~ lake~~s~~ outlines due to shadow in ~~the~~ Corona imagery were evaluated~~assessed~~ using slope data from the Corona DEM; areas~~regions~~ with slopes~~less than~~ ≤10° ~~slope~~ in uncertain zones were ~~cautiously~~ included as lake area only when~~if~~ visually plausible, otherwise they were excluded to avoid~~prevent~~ overestimation. Snow-covered and cloud-covered areas did not affect lake mapping~~,~~ because ~~as~~ they did not ~~were~~ coincide with ~~areas without glacial~~ lake~~s~~ locations.

We applied~~implemented~~ a series of pre-processing steps in ArcGIS Pro to ensure ~~both~~ spatial and spectral consistency between Landsat 7 and Sentinel-2 images. For stable land areas, we confirmed~~verified~~ that pixel values from both~~the two~~ sensors were comparable and that normalized difference vegetation index (NDVI) values indicated similar vegetation cover, thereby ensuring ~~. These checks confirmed~~ that the datasets were suitable for temporal comparison~~could be reliably compared for subsequent analysis.~~ For image composition, ~~we selected~~ Landsat 7 bands 1, 2, and 3 were used to create an RGB composite ~~suitable~~ for water detection~~feature delineation~~, and ~~mapped~~ lake outlines were mapped from Sentinel-2 imagery (10 m resolution) using the corresponding visible bands ~~1, 2, and 3~~. To maintain consistency in ~~glacial~~ lake detection across the multitemporal imagery, we adopted~~set~~ a minimum mapping threshold of 0.00045 km², equivalent to two pixels of 15-m Landsat image, and ~~. This threshold was uniformly~~ applied this uniformly to Corona, Landsat 7, and Sentinel-2 datasets~~,~~, ~~thus~~

permitting temporal comparisons of lake area change. After manual delineation of lake boundaries, we calculated lake parameters areas and classified each lakethem as either contactless or glacier-contact types. Area changes for individual lakes were quantified for the years 1968, 2000, and 2021, and temporal shifts in lake type composition over time were also assessed.

Although manual mapping of lake polygons yields higher accuracy than semi-automated techniques, it remains sensitive is subject to image- quality limitations issues such as boundary ambiguousity margins at lake edgesmargins (Hanshaw and Bookhagen, 2014). This ambiguity arises because pure- -water pixels often borderadjoin mixed pixels containing both water and land, making edgeprecise classification difficultof edge pixels challenging. To estimateaccount for area these uncertainties, we followed the method of Hanshaw and Bookhagen (2014) andto excluded lakes with highly estimate area error, and excluded lakes with ambiguous boundaries from furtherour analysis. To evaluatefurther assess sensor-related uncertainty, we selected a stable reference lake outside the GMC zone that was, clearly visible in all image types. Manual delineation uUsing consistent NDWI-based thresholds, we manually delineated this lake for each sensor and compared the mapped area enabled direct comparison of mapped lake areas across sensors. The analysis showed that Landsat 7 yielded produced slightly larger lake areas estimates than the 1968 Corona reference (absolute difference: 0.000326 km²; relative difference: 8.8%), whereas Sentinel-2 (2021) provided results closer to the referencebaseline (absolute difference: 0.000127 km²; relative difference: 3.4%). The finersuperior spatial resolution of Sentinel-2 contributed to a more precise delineation. An uncertainty of about Nevertheless, an 8.8% was considered uncertainty margin is generally acceptable for manual glacial lake mapping when using Landsat data, and and manual mapping. Consequently, we adopted this reference lake was used to represent for estimating overall sensor-related erroruncertainty. The consistency of these estimates with findings with our previous work in the Kyrgyz Range supports the robustness of our approach (Daiyrov et al., 2022) further validates the approach.

Glaciers were also manually mapped using Corona KH-4 imagery from 1964 and 1968, as well asand Sentinel-2 imagery from 2021. Only scenes with images acquired under minimal cloud and snow cover were usedselected for analysis to ensure reliable accurate boundary identification. All Corona images from 1968 and Sentinel-2 scenes from 2021 were acquired in captured during the summer months (August for Sentinel-2, August- and September for Corona), thereby minimizing the influence of seasonal snow effects (Table 1). Glacier outlinesboundaries were delineated by visual interpretation of standard false-colorcolour composites constructed from multi-spectral imagery, and . Gglacier area changes between 1964/1968 and 2021 were then quantitatively calculated from based on these polygonal outlinesdatasets.

Table 2: List of Satellite images for glacial lake extraction.

Satellite	Sensor	Date	Ground resolution (m)	ID:
Landsat 7	Enhanced Thematic Mapper (ETM)	07.07.2000	30	LE07_L1TP_151031_20000707_20200918_02_T1
		07.07.2000	30	LE07_L1TP_151030_20000707_20200918_02_T1
		16.07.2000	30	LE07_L1TP_150030_20000716_20200918_02_T1
		16.07.2000	30	LE07_L1TP_150031_20000716_20200918_02_T1
		30.07.2000	30	LE07_L1TP_152031_20000730_20200917_02_T1
		30.07.2000	30	LE07_L1TP_152030_20000730_20200918_02_T1
		24.08.2000	30	LE07_L1TP_151031_20000824_20200918_02_T1
		24.08.2000	30	LE07_L1TP_151030_20000824_20200917_02_T1
		02.09.2000	30	LE07_L1TP_150031_20000902_20200917_02_T1
		02.09.2000	30	LE07_L1TP_150030_20000902_20200918_02_T1
Senitnel-2	Multi-Spectral Instrument (MSI)	24.07.2021	10	S2A_MSIL2A_20210724T054641_N0500_R048_T43TEH_20230220T005731.SAFE
		11.08.2021	10	S2B_MSIL2A_20210811T055639_N0500_R091_T43TCH_20230215T033526.SAFE
		11.08.2021	10	S2B_MSIL2A_20210811T055639_N0500_R091_T43TCG_20230215T033526.SAFE
		11.08.2021	10	S2B_MSIL2A_20210811T055639_N0500_R091_T43TDH_20230215T033526.SAFE
		11.08.2021	10	S2B_MSIL2A_20210811T055639_N0500_R091_T43TDG_20230215T033526.SAFE
		11.08.2021	10	S2B_MSIL2A_20210811T055639_N0500_R091_T43TEH_20230215T033526.SAFE
		21.08.2021	10	S2B_MSIL2A_20210821T055639_N0500_R091_T43TCH_20230210T193704.SAFE
		21.08.2021	10	S2B_MSIL2A_20210821T055639_N0500_R091_T43TCG_20230210T193704.SAFE
		21.08.2021	10	S2B_MSIL2A_20210821T055639_N0500_R091_T43TDH_20230210T193704.SAFE
		21.08.2021	10	S2B_MSIL2A_20210821T055639_N0500_R091_T43TDG_20230210T193704.SAFE
		21.08.2021	10	S2B_MSIL2A_20210821T055639_N0500_R091_T43TEH_20230210T193704.SAFE
		05.09.2021	10	S2A_MSIL2A_20210905T055641_N0500_R091_T43TCG_20230118T130151.SAFE
		05.09.2021	10	S2A_MSIL2A_20210905T055641_N0500_R091_T43TEH_20230118T130151.SAFE
		07.09.2021	10	S2B_MSIL2A_20210907T054639_N0500_R048_T43TEH_20230118T203059.SAFE
		27.09.2021	10	S2B_MSIL2A_20210927T054639_N0500_R048_T43TEH_20230124T140016.SAFE

~~To map~~ GMCs in the study area were mapped based on ~~, we employed~~ several geomorphological criteria. GMCs were identified as continuous~~,~~ debris-covered surfaces, up to 3 km long~~,in length~~ extending from the glacier fronts, lacking distinct~~prominent~~ moraine ridges, and showing~~exhibiting~~ a convex cross-sectional profile. The absence or~~of~~ ~~contin~~discontinuity~~uous~~ of surface~~valley bottom~~ drainage channels at glacier fronts was checked ~~through interpretation o~~ from~~f~~ Google Earth imagery. ~~We also assessed t~~The presence of preserved ice within GMCs was further assessed using differential interferometric SAR (DInSAR) ~~analysis~~ to detect surface deformation. These GMCs formed~~developed~~ during glacier retreat after ~~since~~ the Little Ice Age and typically consist of ~~comprise various moraine landforms and buried~~buried ice and debris (Shatravin, 2007; Erokhin, 2011). GMCs boundaries were delineated according to these geomorphological characteristics and existing ~~boundaries established in previous~~ regional mapping~~studies~~ (Maksimov, 1982; Maksimov and Osmonov, 1995; Shatravin and Stavisski, 1984; Shatravin, 2007; Erokhin, 2008, 2011). GMC ~~boundaries~~ were manually digitized primarily from ~~using~~ Sentinel-2 imagery acquired~~from~~ in 2021, and ~~; where image clarity was insufficient,~~ higher-resolution Corona KH-4 images from 1964 and 1968 were used where Sentinel-2 image quality was insufficient.~~referenced to refine the delineations~~. All area delineations were carried out ~~mapping uti~~using ~~lized~~ false~~- color~~colour multi-spectral composites ~~imagery~~ acquired under conditions of ~~with~~ minimal cloud and snow cover.

3.3 Geomorphological analysis using DInSAR

To quantify ~~the number of~~ GMCs containing buried ice, we conducted DInSAR analysis using GAMMA SAR software and ALOS/Phase Array type L-band Synthetic Aperture Radar (PALSAR) and ALOS-2/PALSAR-2 (L-band) datasets. GMCs ~~exhibiting~~ showing surface displacement, expressed ~~— identified~~ as coherent interference~~displacement~~ fringes representing ~~both~~ horizontal and vertical ground motion~~vements,~~ ~~—~~ were interpreted as likely containing significant ice content. These ~~D~~displacement fringes ~~, revealed in the DInSAR results,~~ indicate active surface processes such as permafrost creep or ~~the~~ subsidence resulting from ~~the~~ melting of buried ice. In addition, landform features such as thermokarst depressions, curved ice cliffs, and surface channels were considered in the mapping of GMCs. The processing ~~technical approach~~ and interpretation follow~~ed~~ established method~~sologies~~ from ~~detailed in~~ previous studies~~works~~ (Goldstein et al., 1997; Werner et al., 2001; Quincey et al., 2007; Sandwell et al., 2008; Daiyrov et al., 2018).

~~Our analysis employed b~~Both long-interval (>10 months, spanning winter) and short-interval (1–3 months, summer) interferometric ~~image~~ pairs were~~,~~ used, comprising 49 images in total (18 from ALOS/PALSAR images from~~,~~ 2009–2010 and~~;~~ 31 ~~from~~ ALOS-2/PALSAR-2 images from~~,~~ 2014–2016), all with perpendicular baselines <~~less than~~ 1,500 m (Table 3). ~~Table 3 provides a part of list of image pairs used.~~ The DInSAR ~~processing~~ workflow included~~consisted of~~ converting raw SAR data to Single Look Complex (SLC) format, coregistration~~ering of image pairs~~ ~~SLCs~~, generation~~ng~~ of differential interferograms, removal~~ing~~ of topographic phase using Shuttle Radar Topography Mission (SRTM) DEM, phase unwrapping ~~interferometric phase~~ to obtain displacement~~, information,~~ and geocoding ~~results in~~to a geographic coordinate system. Noise from temporal and spatial decorrelation was reduced~~suppressed~~ using an adaptive filter (Goldstein et al., 1997; Goldstein and Werner, 1998). In our results, ~~displacement fringes in~~ long-interval interferograms mainly captured ~~pairs primarily record~~ slow subsidence, whereas~~ile those in~~ short-interval interferograms~~pairs~~ highlighted ~~reveal~~ more rapid surface motion, consistent with~~. This distinction follows~~ earlier observations from ~~findings, such as those for the Swiss Alps' Gruben~~ rock glacier such as the Gruben rock glacier in the Swiss Alps, where only short-interval interferograms clearly ~~successfully~~ detected surface motion (Strozzi et al., 2004).

DInSAR in high mountains is subject to limitations such as low scatterer density, atmospheric disturbances, and line-of-sight constraints, which can obscure displacement signals (Schlögl et al., 2022). Although L-band data have advantages over shorter wavelengths, issues such as low coherence, shadow, and foreshortening stull affect the results in steep terrain (Atwood et al., 2010; Chen et al., 2025). To validate~~erify~~ the interpretation of buried ice within GMCs ~~based on DInSAR~~, we compared DInSAR-derived surface motion ~~signals~~ at the Chelektor Glacier front with locations of known internal ice ~~occurrences,~~ and found a good spatial correspondence~~that internal ice consistently corresponded with DInSAR detected displacement~~. Additional validation ~~ground truthing~~ was provided by ~~performed using~~ GNSS measurements at the Adygine Glacier GMC, which ~~further~~ support~~ed~~~~ing~~ the ~~interpretation. The~~ presence of active, ice-related deformation. Independent evidence from DInSAR and field survey ~~in GMCs has also been confirmed~~ in the Teskey Range has also confirmed ice-rich GMCs in~~of~~ the northern Tien Shan ~~by both DInSAR and field surveys~~ (Daiyrov et al., 2018). Areas showing~~of~~ pronounced deformation were

also analyzed using DEM differencing (HMA, 2017 and UAV, 2018), which indicated substantial surface changes ~~coincident~~ with mapped buried ice zones. Consequently~~Thus~~, ~~DInSAR detected~~ deformation detected by DInSAR in GMCs~~moraine complexes~~ is interpreted as evidence of ice-rich conditions, with melt-induced subsidence as the most plausible~~probable~~ mechanism (Daiyrov et al., 2018).

Table 3: List of ALOS data (a part of data).

Pair	Master ID	Slave ID	Master Date (YYYYMMDD)	Slave Date (YYYYMMDD)	Span (days)	Bperp (m)	Orbit	Offnadir angle(°)
A	ALOS2015180840-140903	ALOS2058650840-150624	20140903	20150624	294	100.4	Ascending	36.2
B	ALPSRP239030840	ALPSRP245740840	20100720	20100904	46	337	Ascending	34.3
C	ALPSRP079740840	ALPSRP240780840	20070724	20100801	1104	1332.7	Ascending	34.3
D	ALOS2064120840-150731	ALOS2074470840-151009	20150731	20151009	70	90.9	Ascending	32.5
E	ALOS2018580840-140926	ALOS2072400840-150925	20140926	20150925	364	-14.2	Ascending	28.2
F	ALPSRP236550840	ALPSRP243260840	20100703	20100818	46	143.3	Ascending	34.3

3.4 Geomorphological analysis using DEMs and their accuracy assessment

Widespread formation of surface depression (thermokarst feature) on glaciers and GMCs is attributed to surface subsidence caused by melting buried ice (Erokhin et al., 2017; Narama et al., 2010, 2018; Daiyrov et al., 2018; Daiyrov and Narama, 2021). To investigate long-term morphological changes of GMCs, we compared DEMs derived from Corona ~~in~~ (1968) and HMA DEMs (2017). In addition, ~~to investigate morphological changes of GMC, field surveys using~~ unmanned aerial vehicle~~s~~ (UAV~~s~~) surveys were conducted for GMC at~~in~~ the Chelektor Glacier in the~~,~~ central part of the Kyrgyz Range in the summers of 2018 (15 July) and 2023 (28 July), generating complementary high-resolution data. The 2018 survey~~campaign~~ mapped the entire GMC, whereas 2023 survey focused mainly on the glacier terminus because of ~~coverage was partial due to unfavorable~~unfavourable weather~~., focusing primarily on the glacier terminus.~~ UAV data acquired by a ~~The~~ Phantom4 RTK platform (DJI) were ~~captured geotagged imagery~~ processed in Pix4Dmapper to generate~~yield~~ orthoimages with a~~t~~ spatial resolution of 5.4 m and DEMs with a resolution of ~~at~~ 1.0 m ~~resolution~~.

Vertical changes were quantified by ~~Finally, the amount of vertical decline was calculated by~~ comparing multiple DEMs: Corona (4.1 m resolution, 1968), SRTM (30 m, 2000), HMA (8 m, 2017), and UAV DEMs (1.0 m, 2018 and 2023). Surface depression polygons for 1968, 2000, 2017, 2018, and 2023 were generated using a hydrologic 'filling' algorithm in ArcGIS Pro to allow quantitative~~ly~~ assessment of depression area changes over time. The vertical accuracy of these datasets was evaluated relative to the ~~against~~ HMA DEM, which was used as a stable~~provides an accurate, temporally consistent terrain~~ reference. Stable, nonglacier terrain outside ~~areas devoid of glacier and~~ GMCs was~~ere~~ selected as benchmark areas, and ~~s. E~~elevations ~~data~~ from ~~the~~ Corona, SRTM, and UAV DEMs were vertically aligned to match HMA reference elevations, ~~to~~ correcting systematic ~~vertical~~ offsets. ~~Subsequently, e~~Elevation differences between each corrected DEM and the HMA DEM ~~of the corrected DEMs~~ were then calculated ~~computed~~ within polygon area around the stable reference points. ~~The~~ Root Mean Square Error (RMSE) values were ~~within acceptable ranges for geomorphological analysis:~~ 2.2 m for Corona DEM, 2.8 m for SRTM DEM, and 1.3 m for UAV DEM, which are acceptable for geomorphological analysis at the study scale and given the

local relief.~~.~~ However, the relatively sparse GCPs for Corona and the coarse resolution of SRTM limit the ultimate vertical precision of these datasets. ~~These error margins are appropriate considering the study scale and the terrain's elevation gradients, although Corona's limited GCP density and SRTM's coarse resolution limit their ultimate vertical fidelity.~~

4 Results

4.1 Changes in glacial lake numbers and areas during 1968–2021

We identified 274 glacial lakes in 1968, 380 lakes in 2000, and 412 lakes by 2021 (Fig. 2), ~~demonstra~~indicating that the total number of ~~glacial~~ lakes in the Kyrgyz Range ~~effectively~~ nearly doubled over the study period. Of the ~~original~~ 274 lakes present in 1968, 190 (69%) had disappeared by 2000, and~~.~~ ~~Similarly,~~ of the 380 lakes mapped~~observed~~ in 2000, 142 had disappeared by 2021. In contrast, 84 lakes ~~have~~ persisted from 1968 through 2021. Substantial renewal occurred:~~, with~~ 154 new lakes (41% of the total in 2000) appeared between 1968 and 2000, and a further 175 new lakes (42% of the total in 2021) formed between 2000 and 2021~~observed in each subsequent time step~~. Notably, one lake that had vanished by 2000 reappeared by 2021 (Fig. 2). The high rates of both lake disappearance and ~~new~~ formation indicate~~suggests~~ a highly dynamic regime~~process~~ of glacial lake renewal, in~~which~~ contrast~~s~~ to the more gradual and continual expansion of glacial lakes ~~observed in~~reported for the eastern Himalayas since the mid-twentieth century (Yamada, 1998; Ageta et al., 2000; Iwata et al., 2002; Komori et al., 2004). ~~This study used >0.1 km2 threshold and they got 773 lakes. By contrast, there is no lakes of >0.1km2 in our study area.~~ This pattern of rapid lake formation and loss is consistent with trends reported for the Kungoy and Ili Ranges, also within the northern Tien Shan (Narama et al., 2009).

Figure 3 ~~illustrates~~ shows the distribution of lakes by size class over time. In 1968, small lakes (0.00045–0.001 km²) ~~comprised~~ accounted for 36% of all glacial lakes, but ~~while by 2000 and 2021,~~ this proportion declined~~had decreased~~ to 18–22% in 200 and 2021. Medium-sized lakes (0.001–0.01 km²) dominated total lake area~~the area spectrum~~, contributing~~accounting for~~ 60% of the total lake area in 1968, ~~rising to~~ 78% in 2000, and 71% in 2021. The number of large lakes (0.01–0.1 km²) increased from 11 in 1968 to 30 in 2021, and the total area of these lakes expanded 2.6-fold, from 0.23 km² to 0.59 km². A total of 773 glacial lakes larger than 0.1 km² have been identified in the Bhutan Himalayas (Nagai et al., 2017), whereas no glacial lakes exceeding 0.1 km² are present in the Kyrgyz Range.

The cumulative ~~glacial~~ lake area increased from 0.80 km² in 1968 to 1.20 km² in 2000, and then by a further 18% to 1.42 km² by 2021~~by 2021, the area had increased by an additional 18% to reach 1.42 km²~~. Among the 84 lakes that persisted for the entire study period, ~~area changes were significant:~~ 14 exhibited marked~~substantial~~ variability, with area changes ~~ranging~~ from 0.005 to 0.053 km² between 1968 and 2021. Of the lakes present in 2000, 152 experienced areal variation, including 13 with marked increases (0.005–0.053 km²) between 2000 and 2021. Spatial analysis ~~further~~ shows that the largest lakes predominantly formed at the termini of retreating glaciers, while most medium and small lakes developed on GMCs farther from present~~active~~ glacier te~~m~~rmini ~~ice~~.

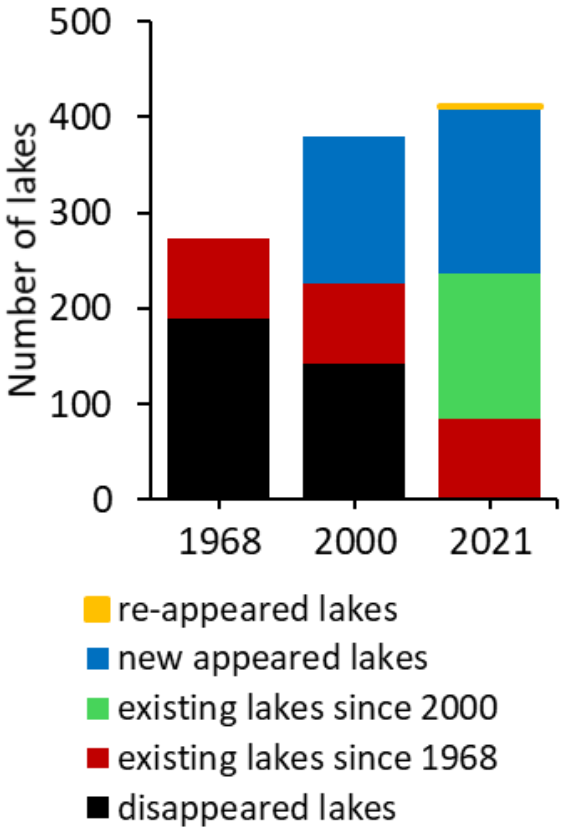

Figure 2. Numbers of glacial lakes and their changes in 1968, 2000 and 2021.

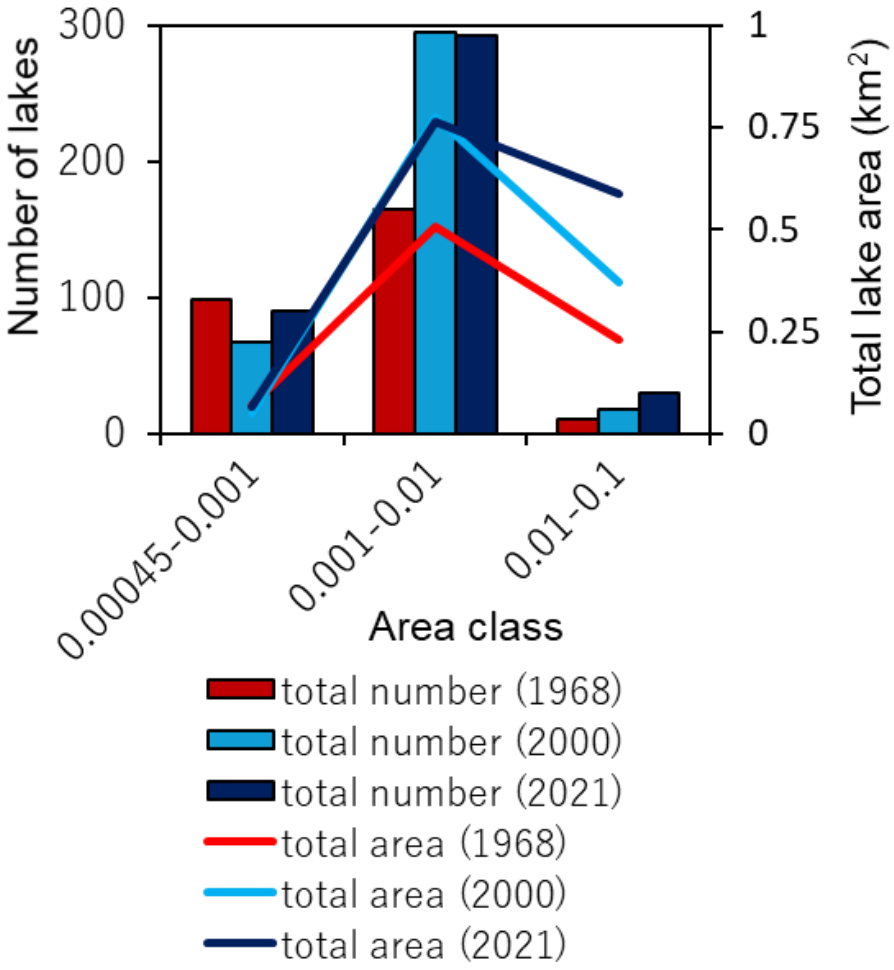

Figure 3: Numbers and areas of glacial lakes in the three area classes in 1968, 2000 and 2021.

4.2 Types of glacial lakes and their evolution

In this region, glacial lakes were classified into two main ~~principal~~ types based on their spatial relationship to glaciers: glacier-contact (proglacial) lakes and contactless (thermokarst) lakes (Fig. 4a). The classification was determined solely by the current location of each lake relative to the glacier margin, rather than differences in genesis. Glacier-contact lakes are situated adjacent to glacier termini and are typically impounded by GMCs, moraines, or bedrock. In contrast, contactless lakes—primarily thermokarst in origin—form on the surface of GMCs as a result of the melting of buried ~~glacier~~ ice. Some thermokarst lakes ~~exhibit~~ show pronounced seasonal variations in surface area, including phases of stability, expansion, ~~contraction~~shrinkage, appearance~~emergence~~, disappearance, and short-lived existence (Daiyrov et al., 2018), similar to ~~phenomena often observed in~~ supraglacial lakes on debris-covered glaciers due to their connection with evolving drainage channels (Narama et al., 2017;

Sakurai et al., 2021) (Daiyrov et al., 2018). In addition, More detailed lake classifications of the lakes infor the study area can be foundhave been presented in previous reports (Erokhin, 2008, 2011; Janský et al., 2006, 2010).

Long-term analysis reveals a notable shift in lake types over time (Fig. 4b). While 45% (124 oOf the 274) of the lakes identified in 1968, 45% (124 lakes) were contactless, increasingthis proportion rose to 72% (272 of 380) in 2000 and 71% (291 of 412) in 2021, indicating a significant increase in the number of thermokarst lakes on GMCs. Conversely, the number of glacier-contact lakes has steadily decreased since 1968. As illustrated in Fig 4c, the fate of individual lakes underscores these trends: of the 150 glacier-contact lakes present in 1968 (including one documented in 1964), only 26 remained classified as glacier-contact lakes by 2021, 36 had transitioned to contactless status due to glacier retreat, and 88 had disappeared altogether. Of the 124 contactless lakes identified in 1968, 55 persisted through 2021 while 70 ceased to existdisappeared.

These results highlight indicate that, unlike the eastern Himalayas—where glacier-contact lakes can persist and expand over extended periods (Yamada, 1998; Nagai et al., 2017)—glacier contact such lakes in the Kyrgyz Range tend to be transient. Here, rRapid glacier retreat combined with generally steeper glacier-front slopes tends to separate former contact lakes from glacier termini, andwhile the limited development of large GMCs and flat outwash plains further constrainsimpedes the sustained expansion and longevity of glacier-contact lakes (Agarwalet al., 2023).

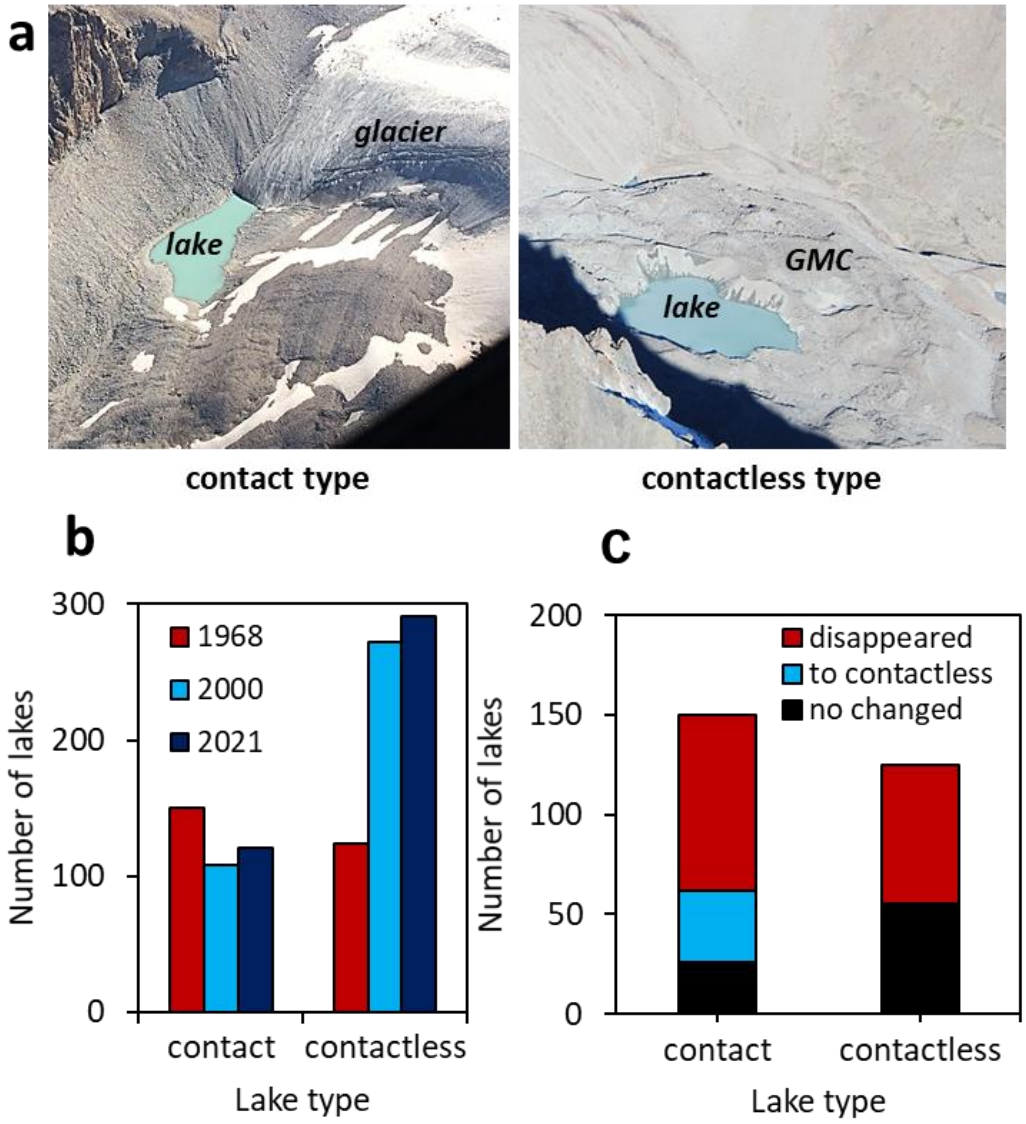

Figure 4: a) Photographs of the two types of glacial lakes: glacier-contact (left); contactless (right) . b) Comparison of the number of glacial lakes by type in 1968, 2000, and 2021. c) Transitions in lake type from 1968 to 2021.

4.3 Area changes in glaciers and surface changes in GMCs

To clarify~~elucidate~~ the processes behind~~underpinning~~ the recent formation and disappearance of glacial lakes, ~~we analyzed~~ temporal changes in both glacier extent and ~~glacier-moraine complexes (~~GMCs~~)~~ were analyzed~~across the Kyrgyz Range between~~ for the period 1968~~ and~~ 2021. Substantial retreat of glacier termini occurred across the range, converting ~~throughout this period, resulting in the transformation of~~ recently deglaciated ~~terrain~~area into GMCs (Fig. 5a). The total glacier area

decreased from ~~390~~378.~~53~~ km² in 1968 to 26~~25~~.~~4~~ 0 km² in 2021, reflecting a reduction of ~~32~~31% over 53 years (Fig. 5b). Spatially, ~~72~~70% of the glacierized area was concentrated in the central part of the Kyrgyz Range, while the western and eastern ~~sector~~parts accounted for 19% and ~~9~~10%, respectively. The relative ~~rates of glacier~~ shrinkage rates were ~~30~~37% in the central part~~region~~, ~~36~~27% in the west, and 40% in the east. ~~Our analysis shows that t~~The number of glaciers decreased from 787 in 1968 to 757 in 2021, despite fragmentation of ~~. Although~~Note that many~~some~~ large glaciers ~~have~~are fragmented ~~~~into smaller ones that glaciers, increased~~ing ~~their total~~ glacier counts~~number~~ (Bolch et al., 2015)~~, the overall number of glaciers has nevertheless declined.~~ This is because small glaciers disappeared after separating from larger ~~parent~~ glaciers. Glacier fragmentation often produced~~leads to the formation of~~ multiple GMCs within a single glacier basin, some of which ~~may~~ evolved into independent units as the source glaciers completely disappeared (Shatravin, 2007; Erokhin, 2011). ~~It~~ This process can also favored the formation ~~result in the development~~ of numerous small lakes (Izagirre et al., 2025). However, not all glaciers in the Kyrgyz Range have formed GMCs.

We identified ~~611~~ 521 GMCs in the Kyrgyz Range. Focusing on GMCs that~~, particularly those~~ host ~~to~~ numerous contactless (thermokarst) lakes, ~~, our~~ comparison of DEMs from Corona ~~(~~ ~~in~~ 1968) and HMA ~~(in~~ 2017) showed that ~~112~~250 GMCs (~~18~~41%~~)~~ of the total~~611 521 GMCs in the Kyrgyz Range)~~ experienced substantial surface lowering of −5 to −30 m~~eters~~. ~~Extensive~~ Large vertical declines (−10 to −30 m) were especially widespread~~evident~~ in GMCs ~~with~~in the Sokuluk, Jylamysh, Ala-Archa, Alamudun, Noruz, Issyk-Ata, and Kegeti river basins (Fig. 1). DInSAR data ~~covering~~ for 2007–2010 and 2014–2016 further revealed that ~~450~~ 396 (~~74~~65%) of ~~611~~ 521 GMCs ~~underwent~~ show significant displacement, ~~a signal that is c~~consistent with ~~surface adjustment attributable to the~~deformation driven by melting ~~of~~ buried ice (Fig. 5c; Daiyrov et al., 2018; Daiyrov and Narama, 2021). These DInSAR results also enabled identification of GMCs with high~~strong~~ potential for future lake formation, as showing by displacement patterns on interferograms from summer 2009 and 2010 (Fig. 6). This significant surface changes occurred mainly on GMCs during summer and were closely related to subsidence from buried ice melt and creep of internal ice. The most pronounced deformation was observed in GMCs in the Sokuluk, Ala-Archa, and Issyk-Ata basins, whereas about 20% of GMCs showed no detectable deformation, implying ice-free or only weakly active conditions. Areas without displacement were likely ice-free or degraded area (Buchelt et al., 2024; Kunz et al., 2022, 2025), indicating not all GMCs still contain buried ice.

At the Chelektor Glacier GMC, ~~—~~a representative site in the central part of the range, ~~—~~three surface depressions (thermokarst feature) formed between 1968 and 2017 (Fig. ~~6a~~7a,b). Morphological evidence from ~~, such as~~ imagery and DEM differences~~,~~ clearly shows~~demonstrate~~ that ice melt induced both surface subsidence and depression formation (Fig. ~~6c~~7c). From 2000 to 2021, depression-1 ~~grew~~ expanded substantially (Fig. ~~6d~~7d), and~~;~~ repeat~~comparative~~ photographs from 2015 and 2018 capture~~highlight~~ the~~se~~ rapid morphological changes (Fig. ~~7a~~8a,b). Over a three-year interval, the surface area of the depression nearly doubled. Elevation profiles (Fig. ~~7c~~8c,f) ~~document~~ reveal ~~a~~ maximum surface lowering of −23 m for depression-1 and −28 m for depression-2, indicating substantial~~confirming significant~~ geomorphic modification~~evolution~~. As the Chelektor Glacier retreated, new glacial lakes formed within these depressions, demonstrating the tight coupling~~illustrating the close linkage~~ between glacier ~~dynamics~~retreat, GMC transformation, and lake ~~development~~ formation (Fig. ~~7d~~8d,e).

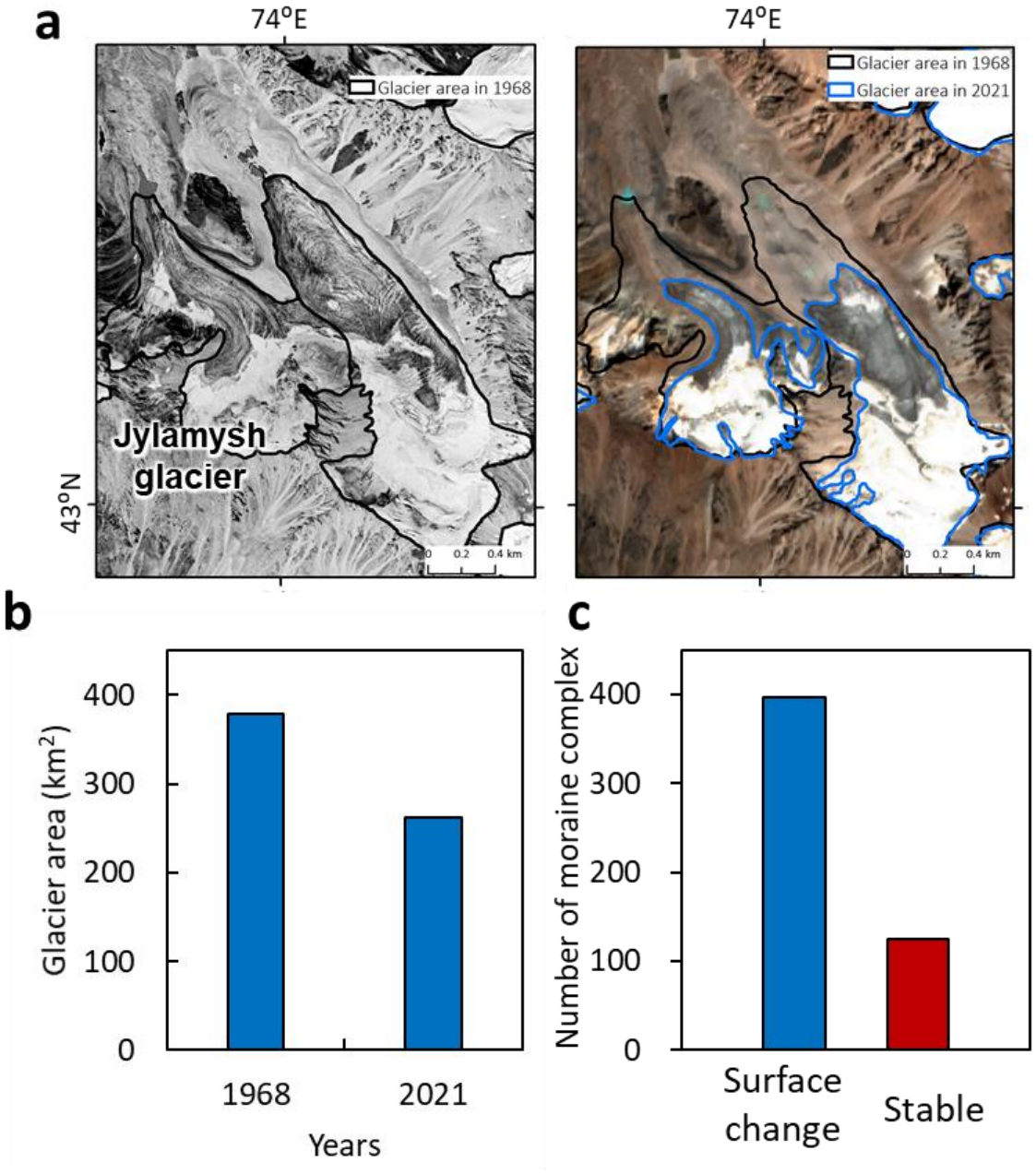

Figure ~~5~~5: a) Glacier shrinkage in the Kyrgyz Range, illustrated by satellite images from different years: Corona KH-4B (1968, left) and PlanetScope (2021, right). b) Changes in glacier area in the Kyrgyz Range between 1968 and 2021. c) Number of GMCs detected at the surface changes based on DInSAR data.

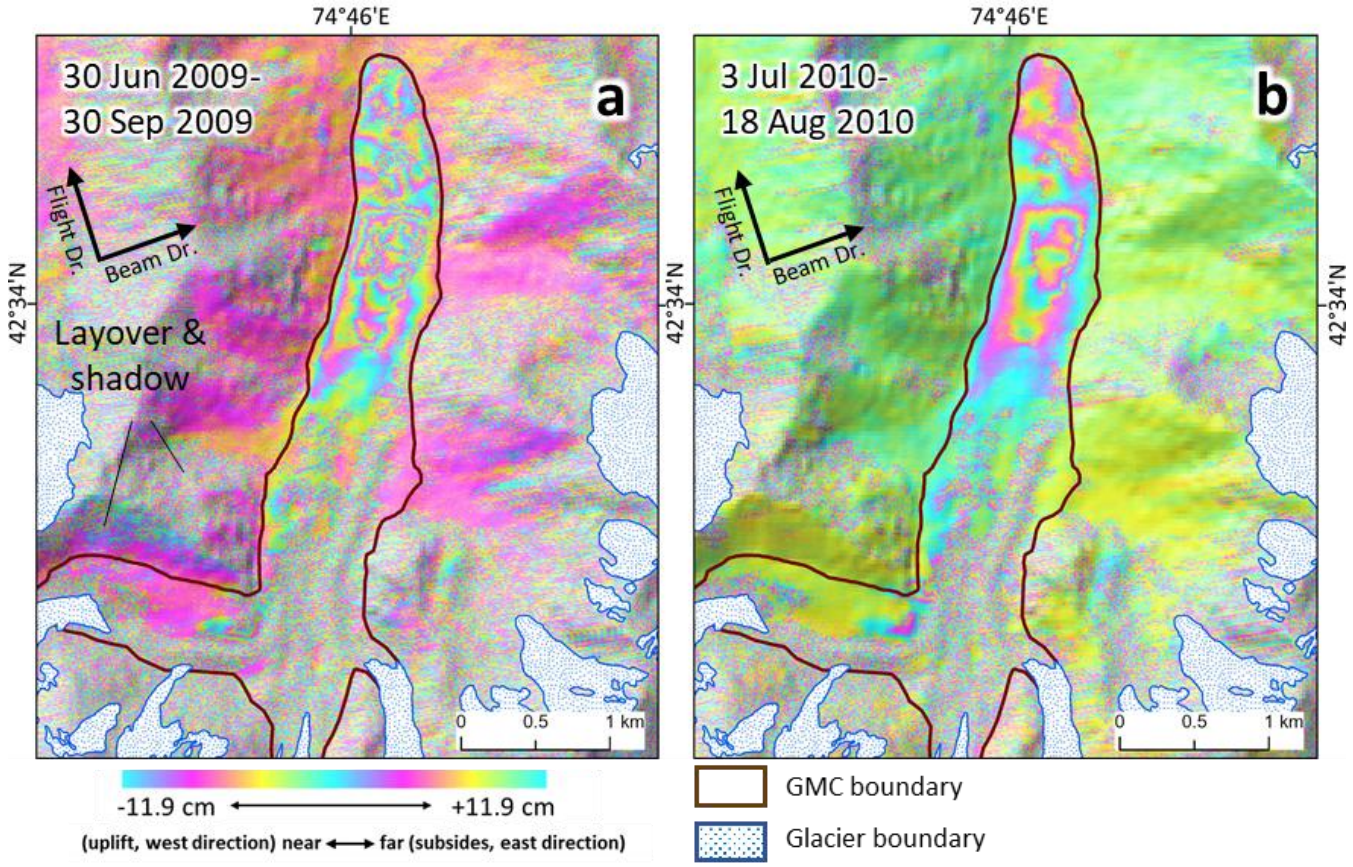

Figure. 6. ~~Aa,~~ b). Seasonal surface change on GMC based on DInSAR analysis in summers of 2009 and 2010 using ALOS/PALSAR (Ken-Tor ~~Noruz~~ GMC, location in Fig. 1). Displacement patterns correspond to subsidence and minor creep movements, interpreted as evidence of buried ice melt and surface instability.

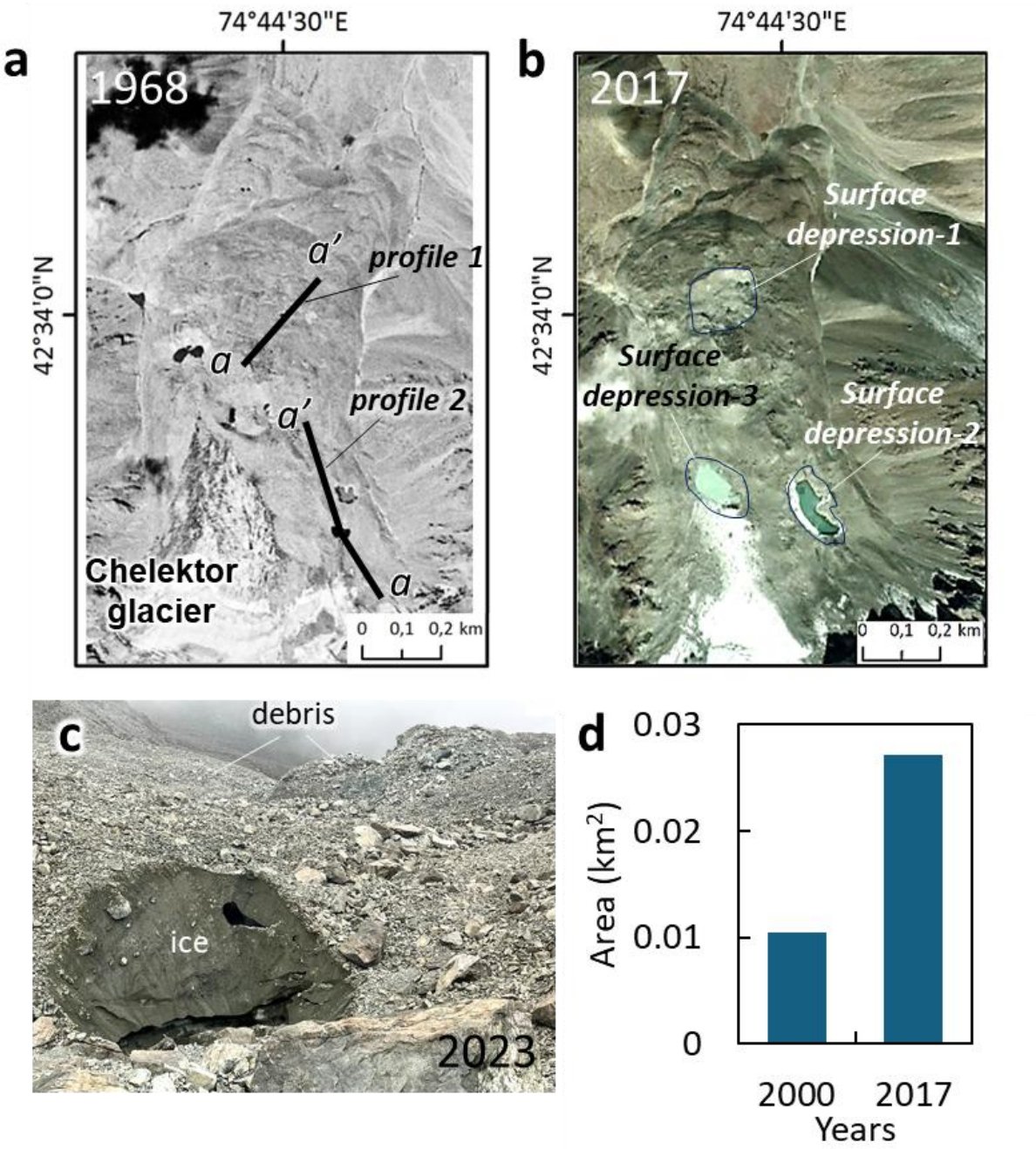

Figure ~~6~~7: a-, b) Development of a surface depression on GMC at the Chelektor Glacier front (location in Fig. 1), illustrated by satellite images from different years: Corona KH-4B (1968, left) and PlanetScope (2017, right). c) Exposed ice on GMC. d) Area changes of surface depression-1 from 2000 to 2017.

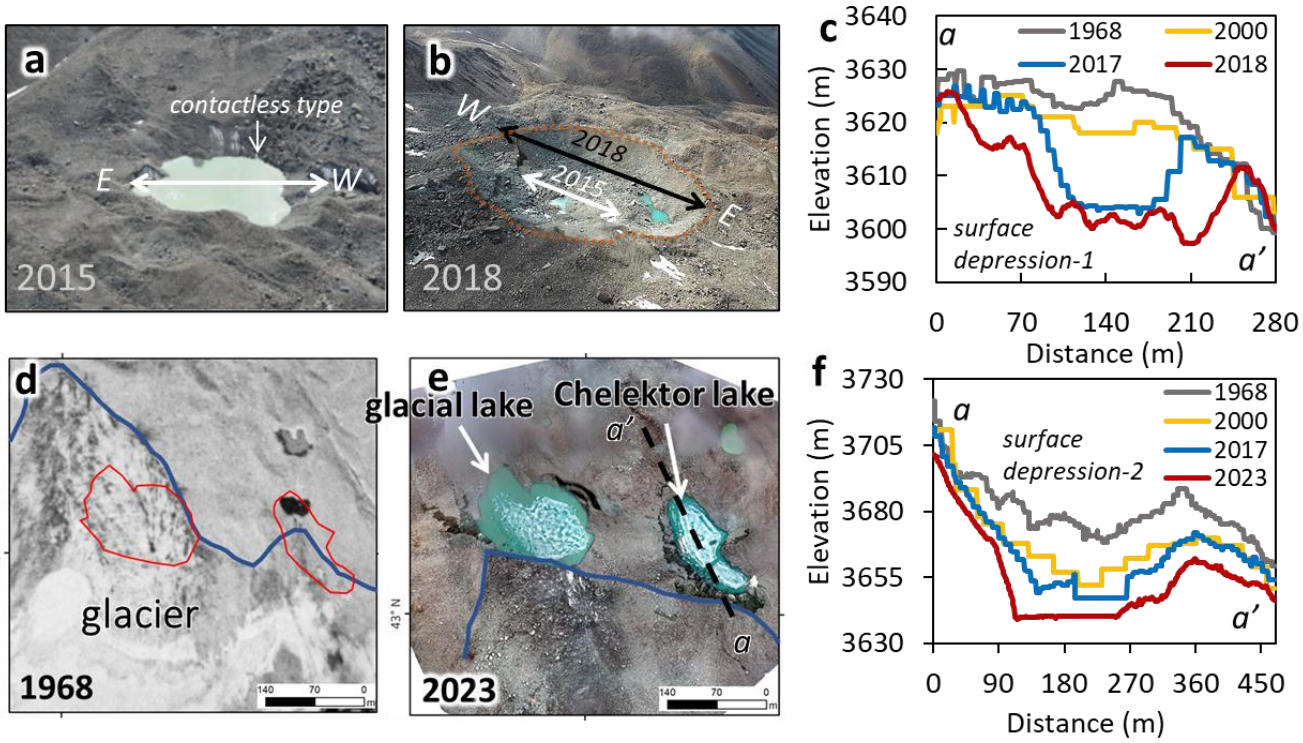

Figure ~~7~~8: Surface depression development and the formation of new glacial lakes on GMC at the Chelektor glacier front. a, b) Photographs of surface depression-1 in 2015 and 2018. c, f) Changes in surface depression profiles (profile lines indicated in Fig. 6a). d) Orthoimage from Corona (1968). e) UAV orthoimage from 2023. Profile data are derived from DEMs of 1968 (Corona), 2000 (SRTM 1), 2017 (High Mountain Asia), and 2018-2023 (UAV data).

4.4 Differences in glacial lake patterns among river basins

~~Figure 8a 9a summarizes t~~The evolution of lake ~~count~~numbers, glacier loss, and GMC area differs among~~for~~ the western, central, and eastern ~~ree sectors~~ parts of the Kyrgyz Range (Fig. 9a)~~, with boundaries shown in Fig. 1~~. In the western and central parts, ~~While glacial lake~~the number of glacial lakes increased steadily ~~in the western and central parts~~regions from 1968 to 2021, whereas a slight decrease in lake number was observed~~recorded~~ in the eastern part. The highest concentration of both glacial lakes and GMCs is distributed in the central part of the range, where glacier loss is also greatest~~larger than others~~.

Focusing on individual catchments in the central part of the Kyrgyz R~~r~~ange (Fig. ~~8b~~9b), most newly formed~~appeared~~~~most~~ glacial lakes are concentrated in the ~~Issyk-Ata,~~ Sokuluk, Ala-Archa, Alamudun~~,~~ and ~~Ala-Archa~~ Issyk-Ata basins,~~catchments~~ . ~~r~~Repeated formation~~development~~ of new surface depressions on GMCs, ~~in the central part~~particularly in the Sokuluk, Jylamysh, Ala-Archa, Alamudun, ~~Noruz,~~ and Issyk-Ata river basins, is~~was~~ associated with significant GMC surface changes and ongoing~~new~~ lake development. In contrast, the Shamshy-North basin in the east and Ak-Suu basin in the western part have more than 30 lakes, while all other catchments have fewer than 30. This concentration of active GMC

evolution and thermokarst lake formation in the central part of the Kyrgyz Range points to it as a key zone for rapid glacial lake renewal and elevated future GLOF hazard potential.

~~highlights the central part of the Kyrgyz Range as a key area for both rapid GMC evolution and ongoing glacial lake formation, particularly thermokarst types engendered by accelerated buried ice melt.~~

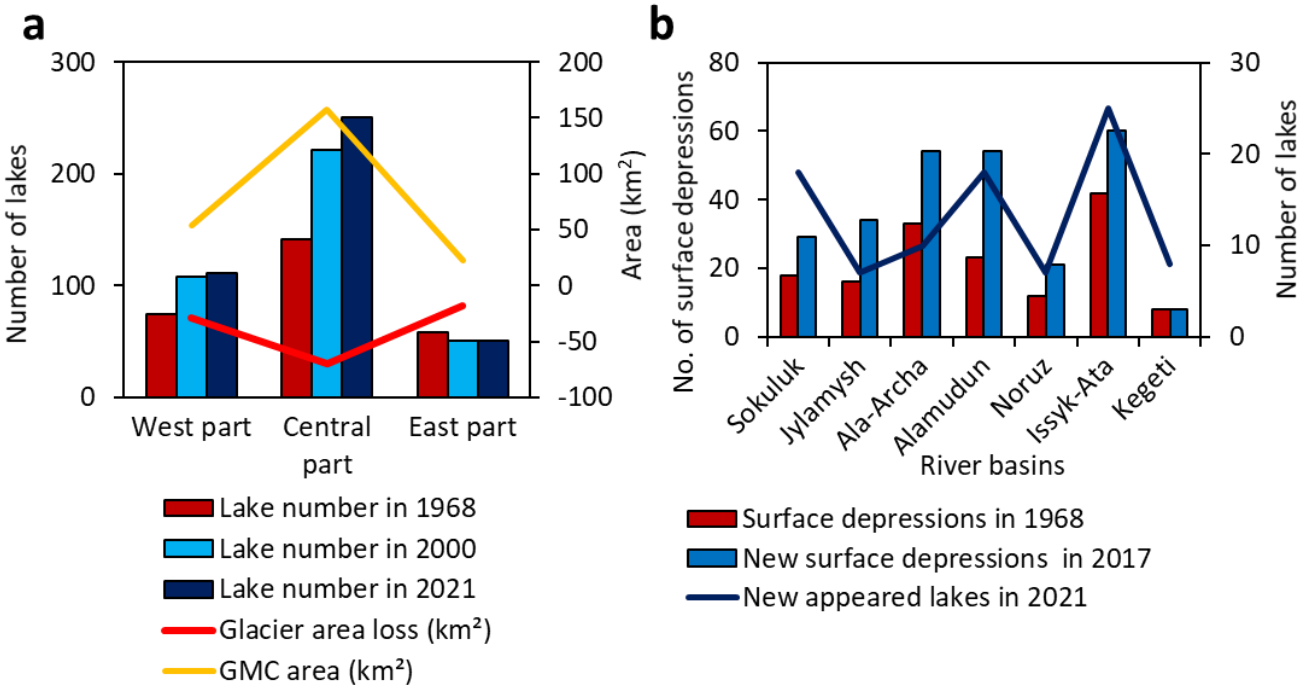

Figure ~~8~~9: a) Number of lakes in 1968, 2000, and 2021, and areas of glacier loss and GMCs in the three sections of the Kyrgyz Range. b) Number of surface depressions in 1968 and 2017, as well as new lakes formed between 2000 and 2021 in the central part of the range.

5 Discussion

5.1 Mechanisms underlying rapid glacial lake renewal

Between 2000 and 2021, 42% of the glacial lakes in the Kyrgyz Range were newly formed (Fig. 2), indicating~~highlighting~~ an exceptionally dynamic lake system. This rapid turnover is consistent with observation~~mirrors trends observed in~~ from the Kungoy and Ili Ranges of the northern Tien Shan (Narama et al., 2009). The primary~~dominant~~ driver is glacier shrinkage~~: —~~glacier area has decreased by about~~approximately~~ ~~30~~31% over the past five decades, and newly ~~degraciated~~deglaciated ~~forefileds~~forcefields have developed into GMCs, greatly expanding ~~. As glaciers retreat, large portions of their forefields become GMCs, leading to the expansion of~~ potential area~~sites~~ for lake formation (Fig. 5a).

The accelerated formation of contactless (thermokarst) lakes is further supported by the observed expansion and deepening of surface depressions (thermokarst features), resulting from the melting of buried ice within GMCs. ~~For example,~~ ~~A~~at the Chelektor Glacier front, both downwasting and backwasting of buried ice have produced pronounced surface lowering and ~~resulted in substantial morphological changes and the~~ lateral enlargement~~expansion~~ of lake basins~~margins~~ (Figs. ~~6~~7, ~~7~~8), similar to ~~. This mirrors~~ geomorphic processes observed on debris-covered glaciers elsewhere (Goldstein and Werner, 1997). Large depressions form~~ed~~ as a result of glacier surface downwasting, as ~~documented~~ reported for~~in~~ the Teskey Range (Narama et al., 2010；Daiyrov et al., 2018), subsequently fill~~ing~~ with meltwater and evolve~~transitioning~~ into glacial lake.

In c~~C~~ontrast~~ing~~ to the eastern Himalayas, where glacier-contact lakes often persist and gradually expand for decades (Yamada, 1998; Ageta et al., 2000; Iwata et al., 2002; Komori et al., 2004; Nagai et al., 2017), glacier retreat in the Kyrgyz Range has ~~mostly resulted in either~~mainly led to the disappearance of contact lakes or their trans~~ition~~formation ~~in~~to contactless types (Fig. 4c). As glacier upslope, ~~Lakes~~ former contact lakes ~~ly connected to glaciers~~ become isolated and lose direct meltwater supply, which frequently ~~as glaciers retreat upslope, no longer receiving direct meltwater input, which often~~ results in their eventual disappearance. The persistence and reappearance of contactless lakes are~~is~~ controlled by~~linked to~~ local geomorphological conditions, including ~~such as~~ the existence of ice tunnels, buried ground ice, and the recurrent formation of surfaces depressions on GMCs. When meltwater or stream channels intersect these depressions, new thermokarst lakes can repeatedly form ~~, sometimes repeatedly~~ at the same location.

Recent climate warming has increased~~greatly enhanced~~ the sensitivity of GMCs to melting, accelerating~~increasing rates of~~ depression formation and thereby~~us~~ promoting additional ~~enabling further glacial~~ lake development (Daiyrov et al., 2018; Daiyrov and Narama, 2021). Consequently, ~~Given these processes,~~ GMCs must be ~~should be recognized~~ regarded as key ~~important~~ environments for ~~driving the~~ future growth~~proliferation~~ of contactless glacial lakes in the Kyrgyz Range~~region~~ (Falatkova et al., 2019). ~~Notably, i~~In the Himalayas, lake development is~~remains~~ more directly associated ~~linked to~~ with glacier shrinkage and the presence of large terminal moraines or broad~~flat~~ outwash plains (Mool et al., 2001a; Iwata et al., 2002; Yamada, 1998; Javed et al., 2025). Ahmed et al. (2021) reported that the expansion rates of pro-glacial lakes connected to glaciers and moraine-dammed lakes are faster than those of other types of lakes. In contrast, the Kyrgyz Range ~~setting~~, with steep glacier forefields and ice-cored moraines, favors ~~promotes more~~ rapid, ~~and~~ recurrent formation of short-lived lakes, a tendency ~~development a trend~~ that likely to intensify ~~accelerate further~~ under continued warming and rising glacier equilibrium ~~–~~line altitudes~~s~~ (Marchenko et al., 2007; Niederer et al., 2008). These~~is~~ features~~highlights~~ underscore the strong control~~influence~~ of glacier retreat and subsequent GMC evolution on the dynamics of glacial lake formation and persistence ~~with~~in the study region.

5.2 Regional variability in lake development

Glacial lake formation and turnover in the Kyrgyz Range strongly~~exhibit~~ concentrated ~~pronounced spatial concentration~~ in the central basins of Sokuluk, Ala-Archa, Alamudun, and Issyk-Ata, where ~~the~~ dense~~density~~ and expan~~dingsion of~~ GMCs coincide with ~~and~~ rapid glacier shrinkage, ~~ladeing~~leading to ~~together foster~~ exceptionally high rates of lake appearance ~~dynamic lake~~

emergence and disappearance, and elevated also increased hazard potential. This central partzone of the range has also experienced mostthe majority of GLOF events over the past two decades20 years (Erokhin et al., 2017; Kattel et al., 2020; Daiyrov et al., 2022), largely most triggered by sudden drainage through ice tunnels within GMCs. TheseSuch processes are characterized by frequent depressions formation and subsequent thermokarst lake development, reflecting the influence of directly linked to ice-rich GMC morphology and the ablation of buried ice. Detailed DInSAR and UAV survey data confirm corroborate this spatial variability, demonstrating that rapid surface lowering onwithin central area of the GMCs in the central part of the range drivesfosters recurrent cycles of lake creation, whereas. By contrast, peripheral river basins with characterized by fewer or more stable GMCs exhibit much more have shown relatively limited changes in theirglacial lake systems.

Similar behaviorbehaviourComparable findings have been reported in nearby regions of the northern Tien Shan. In the Teskey Range, thermokarst lakes exhibit show rapid fluctuations in surface area that are closely associated with GMC conditions, with short-term lake variability linked to persistent ablation of buried ice and frequent transitions among lake types (Daiyrov et al., 2018; Daiyrov and Narama, 2021). Short-term variavilityvariability in glacial lakes has been attributed to persistent ablation of buried ice, resulting in rapid transitions in lake type. Short-livedterm lakes have been responsible for variations caused variability in lake type, and many of them changed under GMC change. Among these lake types, short-lived type caused mmost recent GLOFs in the Kyrgyz and Teskey Ranges, where triggers often involve temporary closure and reopening of ice tunnels within GMCs (Narama et al., 2010, 2018; Erokhin et al., 2017; Daiyrov et al., 2020, 2022). Among these, short-lived lakes have been responsible for most recent GLOFs in both the Kyrgyz and Teskey Ranges. The triggering mechanism for such events since 2000 has often been the temporary closure and reopening of ice tunnels within GMCs. Tunnel blockage maycan result from debris deposition or the freezing of water insidewithin ice tunnels, with debris frequently supplied by melting dead ice in GMCs (Erokhin et al., 2012; Narama et al., 2018; Daiyrov and Narama, 2021)., debris deposition is frequently linked to melting of dead ice within GMCs (Daiyrov et al., 2018; Daiyrov and Narama, 2021). The thThawing of buried ice through thermokarst processes leads to surface subsidence, collapse, and the subsequent formation of distinctive thermokarst lakes (Kääb and Haeberli, 2001). Thus, lake development in the Teskey Range—and likewise in the Kyrgyz Range—is fundamentallystrongly governed by GMC conditions and the presence of large volumes of buried ice.

Given the continued rise inongoing regional warmingtemperatures, further melting of dead ice within GMCs is expectedanticipated, likely causingresulting in additional depression enlargement of depressions, accelerated lake formation, and increased risk of sudden drainage events (GLOFs). Continuous monitoring and hazard assessment focusinged on GMC-rich chatchmentscatchmentsareas, particulralyparticularly—especially those with population areascenters downstream, —are thus essential, even though this study does not explicitly therefore critical, even as this study does not directly model future GLOF scenarios. Nonetheless, our documentation of buried ice GMCs and rapidly evolving lakes offers an important foundation for anticipating and mitigating cryospheric hazards in the Kyrgyz Range.

At the sclalescale of broader High Mountain Asia (HMA) scale, glacial lake expansion and relatedGLOF hazards are being increasingly recognized. Furian et al. (2022) projected the formation of large proglacial lakes across HMA through 2100. Recent studies demonstrated accelerated glacial lake growth and applied moraine-dam outburst models such as the eastern

Himalayas for GLOF risk assessment (Zhang et al., 2023; Chen et al., 2024). However, the processes of lake formation and GLOF triggering in the Tien Shan differ fundamentally from those in the eastern Himalayas. Therefore, effective assessment of disaster preparedness and future projections requires (1) current records of region-specific lake development and GLOF history, and (2) a detailed understanding of the characteristic lake formation processes specific to each mountain region.

6 Conclusions

This study quantifies the dynamic evolution of glacial lakes in the Kyrgyz Range, northern Tien Shan, over the period 1968–2021. During these 53 years, the number of glacial lakes increased from 274 in 1968 to 412 in 2021, ~~, a~~ nearly doubling, ~~—~~ while total lake area expanded by 76%, from 0.80 km² to 1.42 km². Lake ~~T~~turnover was extremely high: of the 274 lakes present in 1968, 190 (69%) had disappeared by 2000. Despite these losses, 154 new lakes appeared by 2000, and 175 more had formed by 2021, with ~~just~~ only 84 lakes persisting throughout~~across~~ the entire study period. Glacier area simultaneously shrank by ~~32~~31% ~~(,~~ from ~~390~~378.~~3~~5 km² to ~~265~~262.~~4~~0 km²~~)~~, driving the widespread formation of ~~glacier–moraine complexes (~~GMCs~~)~~ rich in buried ice. Surface lowering of about~~up to~~ 5-30 m was observed in ~~18~~41% of GMCs, and DInSAR analysis ~~revealed~~ showed that ~~74~~65% of GMCs exhibited~~showed~~ measurable deformation, indicating active adjustment linked to buried-ice melt and favoring the rapid formation of new, often thermokarst, lakes. ~~promoting the rapid development of new, often thermokarst lakes.~~ By 2021, over 70% of all glacial lakes were contactless types, reflecting the predominance of lake formation o~~i~~n GMCs rather than sustained~~over persistent~~ proglacial lake expansion. ~~These processes underpin a regime of constant glacial lake renewal, contrasting with the gradual expansion seen in the Himalayas.~~

In the Kyrgyz Range, glacial lakes renew rapidly due to the combination of accelerated glacier retreat, the expansion of glacier–moraine complexes (GMCs) containing buried ice, and ongoing climate warming. As glaciers shrink, newly exposed GMCs with significant dead ice melt and subside, forming new surface depressions that quickly fill with meltwater to create short-lived lakes. This geomorphological instability, coupled with repeated melting and reformation cycles, leads to a highly dynamic regime where glacial lakes frequently disappear, reappear, or form a new. The central part of the Kyrgyz Range, particularly the Sokuluk, Ala-Archa, and Issyk-Ata basins where many glaciers and GMCs are distributed, remains a hotspot for lake turnover and associated hazards. As warming continues, monitoring lake dynamics and GMC changes will be vital for hazard assessment and adaptation in the region. ~~Integrating DInSAR with optical inventories and field validation remains essential.~~ These findings demonstrate that glacial lakes in the Kyrgyz Range are characterized by continual renewal, driven by the combined effects of accelerated glacier retreat, GMC expansion and degradation, and ongoing climate warming, and that this regime contrasts sharply with the more gradual, persistent lake growth observed in regions such as the eastern Himalayas.

Funding

Grant-in-Aid for Scientific Research (B) (19H01372 and 23K22023) of MEXT KAKENHI Grant.

Acknowledgments

We thank two reviewers for their valuable comments and suggestions. This work was supported by Grant-in-Aid for JSPS Fellows (22F22006) of JSPS KAKENHI Grant and Grant-in-Aid for Scientific Research (B) (19H01372 and 23K22023) of MEXT KAKENHI Grant. This study used ALOS satellite image data from ALOS Research Announcement (RA) in the framework of JAXA EORC.

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