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Documenting glacial changes between 1910, 1970, 1992 and 2010 in the Turgen Mountains, Mongolian Altai, using repeat photographs, topographic maps, and satellite imagery

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The Turgen Mountains lie in northwestern Mongolia, roughly 80 km south of the Russian border. The area was visited in 1910 by a Royal Geographical Society expedition led by Douglas Carruthers. The party undertook an extensive survey of the range and also documented the extent of the glaciers with photographs. One hundred years later, in summer 2010, a US–Mongolian expedition retraced portions of the 1910 expedition. Camera locations were matched to the historical photographs and repeated photographs taken. In addition, the termini of the two main glacial lobes were surveyed by GPS. Analyses of field data, repeated photographs from 1910 and 2010, topographic maps from 1970, and satellite imagery from 1992 and 2010 were used to describe the changes in the glacial system. The results suggest that while the snow and ice volume on the summits appears to be intact, lower elevation glaciers show significant recession and ablation. From 1910 to 2010, West Turgen Glacier receded by *c*. 600 m and down-wasted by *c*. 70 m. This study successively demonstrates the utility of using historic expedition documents to extend the modern record of glacial change.

KEY WORDS: Altai Mountains, glacier, historical geography, Mongolia, repeat photography, remote sensing

Introduction

During the warming of the current inter-glacial period, many glaciers of the world are experiencing pronounced wastage. Regardless of the anthropogenic contributions, the effects of the warming are observable and measurable. Since glaciers are the 'water towers' in alpine environments on which flora, fauna, and often humans depend, a global effort to assess the health of glaciers is underway, to include the Global Land Ice Measurement from Space (GLIMS) programme, the World Glacier Inventory (WGI), and the World Glacier Monitoring Service (WGMS).

It is assumed that the current global climatic shifts have an effect on the glaciers in Mongolia. Surprisingly, relatively little work has been done on these glaciers, and as a consequence, the extent of glacial changes is still unclear (see review and summary by Kamp *et al*. 2013a 2013b). The glaciers of the Turgen Mountains have been the subject of several mapping studies with various results. Using topographic maps generated from aerial photographs and satellite data, Lehmkuhl (1998) concluded that the glaciers had retreated between 200 and 500 m from 1948 to 1991. Employing only remote sensing techniques, Kadota and Davaa (2007) reported that while Turgen Glacier had lost 19% of its surface area between 1970 and

1990, it remained stationary afterwards. Interestingly, another study by Khrutsky and Golubeva (2008) which employed remote sensing found that the glaciers had lost 35% of their area in a similar timespan. There is not inconsistency within these reports but between them which calls to question many possible reasons including methodologies. Further discrepancy may stem from the fact that limited to no fieldwork was used to validate the results of remote sensing analysis.

The existing studies on glacial changes in the Turgen Mountains cover a time period that reaches back to the late 1940s. However, through researching archives, it is possible to extend the baseline using expedition records from before this time. In 1910, a Royal Geographical Society (RGS) expedition under Douglas Alexander Carruthers visited the area. The expedition undertook an extensive survey of the mountains, produced a detailed topographic map, and documented glacier extents with photographs. In order to reconstruct the last century of glacier variations in the Turgen Mountains, a US–Mongolian expedition retraced portions of the 1910 expedition in the summer of 2010, and repeated the pertinent original glacier photographs.

The use of repeat photography was first applied to the study of glaciers in the Alps by Sebastian Finsterwalder in the late nineteenth century (Webb 2007). In general terms, the method requires that previous photo point locations of historical photographs be reoccupied to acquire a new series of photographs which are then used for comparative interpretation of landscape transformation (Nüsser 2001). Rogers *et al.* (1984) compiled a comprehensive summary of reimaging techniques, which were then adopted by the US Forest Service to monitor re-vegetation after wildfire and the expansion of urban zones (Hall 2001). Repeat photography has been extensively used to study environmental changes in mountains, for example, local land-use pratices (Ives 1987; Nüsser 2000), stream changes (Graf 1978; Butler and Malanson 1993), mass movement (Ives 1987; Hincks and Cruden 2003), and snow and glacier changes (Veatch 1969; Hastenrath 2008). No study using repeat photography on the glaciers in Mongolia could be found.

This work offers a unique opportunity to monitor an isolated glacial system in the Mongolian Altai Mountains that has a detailed account in the historical record. The purpose of this study is to describe the glacial change between the years 1910, 1970, 1992 and 2010 by integrating historical data with modern remotely sensed imagery.

Unfortunately, because of copyright reasons, we are unable to publish the 1910 photographs in this paper and, hence, visually document the results of our repeat photography analyses. However, we hope that in the future copyright issues will be resolved and these important documents can be reproduced alongside one another.

Regional setting

The research was conducted in the Turgen Mountains in northwestern Mongolia (Figure 1). The mountains

Figure 1 Location of the study area in the Turgen Mountains in western Mongolia

are heavily glaciated on the northern aspects, feeding several rivers which flow northeast towards the regional capital of Ulaangom and into the Lake Uvs Nuur Basin.

Carruthers (1914a, 276–7) described the mountains as the expedition approached it from the north in 1910:

> With superb grandeur the snow pinnacles rise above the forested valleys and grassy plateaux. From every point of the compass, for many days' journey away, one can see the principal peak, a cone of ice, which rises to over 13,000 ft. [around 3962 m] in altitude . . . As a snow-capped mountain of alpine character, the Turgen stands solitary, rising sharply above the steppes and the desert-ranges which surround it on all sides.

While isolated, the Turgen-Kharkhiraa Mountains (49–50° N, 91–92° E) are generally accepted to be related to the Altai Mountains. However, they are not directly connected; they rise alone over the three lake basins of Uvs Nuur, Uureg Nuur and Achit Nuur, which make up the Mongolian Great Lakes Basin. The two highest peaks are Turgen Nuruu (between 3954 and 3978 m depending on the source) and Kharkhiraa Uul (between 4037 and 4040 m depending on the source) (Lehmkuhl 1999; Khrutsky and Golubeva 2008). The mountains are formed predominately by the strong tectonic uplift of the Altai Mountains, while the forces of glacial erosion carved large U-shaped valleys bordered by cirques and hanging valleys (Khrutsky and Golubeva 2008).

The general climate of landlocked Mongolia is extreme continental and characterised by low temperatures, low humidity, high moisture deficit, and low levels of incident energy (Batjargal 1997). In general, the winters are cold and dry, with the Mongolian anticyclone dominating the regime, perhaps even ablating some summer snow (Khrutsky and Golubeva 2008). Summers are dominated by the Westerlies that bring precipitation from the Atlantic and the Mediterranean, and this is why the Turgen Mountains are known for persistent cloud cover, possibly due to orographic lifting; in contrast, the monsoons from the south are blocked by the Karakoram and Himalaya (Gillespie *et al*. 2003, Khrutsky and Golubeva 2008). A century ago, Carruthers (1914b) remarked how the summer veil of clouds was responsible for the preservation of the large snowpack. Recent studies estimated that up to 70% of the annual precipitation falls during June, July and August (Kadota and Davaa 2007). Much of that precipitation falls as snow in the high elevations of the mountains, where summits can reach to above 4000 m. Without the presence of weather stations within the Turgen Mountains, Khrutsky and Golubeva (2008) estimated that above 2500 m mean annual precipitation is 400–500 mm.

In the valleys of the Altai Mountains the mean temperature is –30 to –34°C in January and less than 15°C in July (Batima *et al*. 2005). For Ulaangom (939 m; 49° 55′ N, 92° 03′ E) located in a basin northeast of the Turgen-Kharkhiraa Mountains, the measured mean annual temperature is –4°C, and the mean monthly temperature ranges between –32°C in January and 19°C in July (Jansen 2010). Böhner (2006) put the mean temperature in the region of the summits at –8°C and the mean monthly temperature range at between –23°C in January and 5°C in July. Jansen (2010) used climate data from 1952 to 1995 from the weather station in Ulaangom to model climate parameters for the Turgen-Kharkhiraa Mountains and concluded that in winter inversions are common with temperature increases of up to 2K 100 m^{-1}; hence, the Turgen-Kharkhiraa Mountains represent a 'heat island' compared with the basin.

From the 1940s until the early 1990s, the mean annual air temperature in Mongolia increased by 1.56°C, particularly because winter temperatures increased by 3.6°C and spring/fall temperatures increased by 1.5°C, while summer temperatures slightly decreased by 0.3°C (Dagvadorj *et al*. 1994; Yatagai and Yasunari 1994; Dagvadorj and Mijiddorj 1996; Dagvadorj and Batjargal 1999; Batima and Dagvadorj 2000). Batima (2006) extended the time period to 1940–2003 and presented an even higher temperature rise of 1.8°C, with clear warming from the beginning of the 1970s intensifying towards the end of the 1980s. With regard to this general warming trend for the entire Mongolia, Batima *et al*. (2005) pointed out that such temperature changes varied both in space and time: from 1961 to 2001 the warming was 4°C in winter and 0.9°C in summer in Khovd in the Altai Mountains, and only 0.8°C in winter and 0.5°C in summer in Dalanzadgad in the southern Gobi. Both Jacoby *et al*. (1999) and Batima (2006) detected a slight increase in precipitation during the second half of the twentieth century; however, the changes were statistically insignificant and within the range of long-term variations.

Depending on the scenario (SRES A2, SRES B2), existing climate change models show a temperature rise of 2–8°C above 2000 temperatures until 2099 for Mongolia, both in summer and winter (Mitchell *et al*. 2002). Compared with the baseline period 1961–1990, for the time slices 2020s, 2050s and 2080s, Batima (2006) presented a future winter warming of 0.9–8.7°C and a summer warming of 1.3–8.6°C; a precipitation change by –3% to 11% in summer, and by 13–119% in winter; a snow cover decrease by 27–51%; and an evapotranspiration increase by 13–91%. However, general precipitation is relatively low, so that such changes reflect relatively small changes in absolute precipitation (Batima *et al*. 2004).

The numbers for glaciers and glaciated area for the Turgen Mountains vary widely in the existing literature (Table 1): for example, using the same aerial photographs, 34 or 40 glaciers were identified for 1991 (Jansen 2010; Lehmkuhl 2012). Carruthers (1912,

Table 1 Glaciated area and number of glaciers in the Turgen Mountains from published references

Year	Source data type	Number of glaciers	Glaciated area (km^2)	Reference
1947–1950, 1972	Aerial and topo	–	48.5	Dashdeleg (1990)/Lehmkuhl (2012)[1]
1948	Topo 1:100,000	–	50.1	Davaa and Kadota (2009)
1948	Topo 1:100,000	–	47.0	Lehmkuhl (2012)
1948, 1950	Topo 1:100,000	29	45.2	Lehmkuhl (1998)
1968	Topo 1:100,000	–	43.0	Kadota and Davaa (2004)
1969	Topo 1:200,000	39	46.8	Khrutsky and Golubeva (2008)
1988	Aerial 1:44,000	–	(~34.7)	Kadota and Davaa (2004)
1988, 1991	Aerial 1:45,000	40	44.0	Klinge (2001)[2]
1991	Aerial 1:45,000	–	40.2	Lehmkuhl (1999)
1991	Aerial 1:45,000	34	35.5	Jansen (2010)
1991	Aerial 1:45,000	40	33.8	Lehmkuhl (2012)
1992	(Satellite or aerial?)	–	51.0	Davaa and Basandorj (2005)
1992	Landsat	39	38.6	Khrutsky and Golubeva (2008)
2000	Landsat	–	34.7	Kadota and Davaa (2004)
2002	(Satellite or aerial?)	–	33.8	Davaa and Basandorj (2005)
2002	Landsat	39	33.7	Khrutsky and Golubeva (2008)
2010	Landsat	–	31.8	Kamp *et al*. (this study)

Source: after Kamp *et al*. (2013b), revised
[1]These data summarised in Lehmkuhl (2012) are based on a map in Dashdeleg (1990)
[2]Glaciated area calculated using data and equation from Klinge (2001): 'glacier length x 0.7 = glaciated area'

534; 1914a, 283) writes that in 1910 old moraines were present one mile from the snouts of the glaciers which 'in all cases, were in a state of retreat', and with the East Turgen Glacier calving in seracs at its terminus. In the modern epoch, the glaciers have retreated to the highest basins and continue to recede (Lehmkuhl 1998 1999 2012). However, recent research has suggested that the rate of ablation stabilised around the end of the twentieth century (Kadota and Davaa 2007).

Materials and methods

Field mapping

The 1910 RGS expedition to the Turgen Mountains was only one small part of the longer journey lead by Douglas Alexander Carruthers (1882–1962). It was one of the last classic Victorian explorations, epitomising the style of English geographers that were 'masters of all they surveyed' (Burnett 2000). These geographers truly 'explored' the landscapes that they moved through, collecting samples of everything that they encountered, and documenting every waking moment. Carruthers' team entered the Turgen Valley on 13 August 1910 and proceeded to head towards the peaks conducting a plane table survey. On the 15 August, they camped on the bench above the Turgen River 'within striking distance of the high peaks' (RGS-IGB Archives 2010).

In 2010, during the archival studies at the RGS-IBG in London notes were taken from the original 1910 expedition diaries and map, and high-resolution scans of the 1910 glacier photographs were collected. On 12 July 2010 the team approached the Turgen Mountains from the shores of Uureg Nuur Lake and then followed the track of the 1910 expedition up-valley towards Turgen Peak. A standard geomorphological mapping was carried out; photographs from the original photo point locations were repeated from several ascended high points and at East and West Turgen glaciers; and various point and line data were collected, including photo point waypoints and tracks around the glacial margins using a consumer grade Garmin 60CSx. A vertical error of 9–12 m was noted, which falls within the resolution of both the satellite and digital elevation model (DEM) data. On the southern reaches of the Turgen Mountains, the Carruthers route was followed on the Yamachu Plateau, but the few remaining 1910 photograph points were too obscure to be repeated.

Maps and satellite imagery

The final product of Carruthers' 1910 survey is a map of the Turgen Mountains at 1:350 000 scale with 500 ft contour intervals. It was originally published in this journal (Carruthers 1912) (Figure S1)[1]. The map represents the landscape with surprising precision; so accurate in fact, that it was used to navigate while trekking through the region during the 2010 expedition. However, cartometric analysis revealed that the 1910 map is distorted considerably towards the north

Table 2 Digital data used in this study

Name	Date	Resolution	Format	Source
Map of the Turgen Mountains by Carruthers	1912	1:350 000	Paper Topographic, Digital Mosaic of pdf Scans	RGS-IBG
Soviet topographic maps M-46-75, M-46-76, M-46-87, M-46-88	Updated 1970, from 1968 Aerial photos	1:100 000	Digital Scans of Paper Sheets	Mapstor
Landsat L5 TM	29 August 2010 and 27 September 2010	30 m	Digital Satellite Imagery	Earth Explorer
Landsat MSS	25 June 1992	60 m	Digital Satellite Imagery	GLCF
ASTER	Various	30 m, 20 m Z	gDEM	WIST
SRTM	2002	90 m	DEM	Earth Explorer
CGIAR SRTM	2002, updated 2010	90 m, 16 m Z	DEM	CGIAR
Mongolian roads, rivers, lakes, villages	Various	Various	GIS Shapefile	Geo Community
GPS field data	July 2010	9–12 m	GPX	Authors

and slightly to the west, and, consequently, is not accurate enough to evaluate the position of the glaciers in 1910.

Soviet Union Generalnyi Shtab 1:100 000 topographic maps were downloaded from the Mapstor web portal (Table 2). The ground surveys for these maps were originally conducted in 1942, and updated in 1949. The area around the Turgen Mountains was updated with aerial photography in 1970 as per the marginal information on the map sheets.

A Landsat MSS scene from 25 June 1992 with a 60 m horizontal resolution was downloaded from the Global Land Cover Facility (GLCF) (Table 2). Landsat 5 TM scenes with a 30 m horizontal resolution were downloaded from the Earth Explorer data portal. A scene from 29 August 2010 is very clear and covers 90% of the 1910 map extent. To cover the missing 10%, the corresponding 10 September 2010 image was substituted.

Digital elevation models

SRTM DEM tiles were downloaded from the CGIAR data portal (Table 2); CGIAR data have been corrected and filled to provide 16 m of resolution in elevation. The CGIAR DEMs were used with the repeated photographs to determine glacial recession over the hundred-year study period.

Glacier mapping

The 2010_L5TM layer was symbolised in a true colour combination of 3-2-1 and then pan-sharpened by a 7-4-2 band combination to aid in visually identifying the glacial extents against the classification calculations. A band ratio analysis (TM4/TM7) was carried out and the result symbolised as two classes using a threshold of 1.9 (Krumwiede *et al*. 2013). There can be a tendency to falsely misclassify debris-covered glaciers, but the Turgen ice is relatively debris free. The final glacier classification was then manually edited for a few small proglacial lakes that had been mistakenly included.

Field repeat photography

Many historic photo locations are not well documented, especially in mountain settings; these areas require extensive fieldwork to reacquire new photographs (Fagre 2010). This is the case with the Carruthers collection from 1910: while the route of his expedition was well recorded, the specific locations of photographs are not marked in the map, nor are they noted in the field journals. The 1910 photo point locations were determined only by careful examination of photograph captions and the occasional non-specific remark in a field book. Through virtual rephotography, Carruthers' route was travelled utilising the 3D model within Google Earth, and the probable photo points were estimated (Webb *et al*. 2010; see below). Once in Mongolia, the 1910 route was followed using GPS paying careful attention to the landscape until a viewpoint could be matched with a printed historic photograph.

The Carruthers expedition carried several cameras and a good supply of film for their two-year journey: Kodak A3 postcard camera, New Newman & Guardia 'Nydia' w/ changing box, Kodak panorama camera, Pack film adapter, 200 plates at 78 speed, 72 Pack films, 72 postcard rolls, and 80 panoramas (RGS-IGB Archives 2010). There are no explanations of how the cameras were used either in the personal diaries or in the published accounts of the expedition. It appears that the cameras were utilised more as a tool for documentation of the journey, and not viewed as scientific instruments. Also, the journals do not mention which camera was used for each photograph. This makes it difficult to determine the focal length for individual pictures and prevents the use of more advanced photogrammetric techniques. There is no credit given to the photographers responsible for specific images. Considering the extended periods that Carruthers spent at the plane table and preparing skins, it is likely that most of the photographs were taken by one of the other two team members, journalist Morgan Phillips Price or professional hunter John Humphrey Miller. In most cases, the photographs in the Carruthers collection are in focus and properly exposed. Some appear to be clearer than others, likely due to the camera model, with the one panoramic of the Turgen Mountains being the sharpest. Most of the photographs are of a cultural nature, consisting of portraits of the various ethnic groups encountered along the way. The scenes of landscape photography seem to have been chosen purely by the vistas which most inspired the expedition members. The majority of scientific investigation was concentrated on collection and preparation of geologic, botanical and taxidermy samples.

Unfortunately, the RGS-IGB archives have only prints of the 1910 Carruthers expedition photographs, and these prints are almost a century old. There are two pages covering the Turgen portion of the expedition in a large format album that contains hundreds of photographs (around 4 × 3 inches) that are mounted to the pages with glue and are in fair condition, showing some staining and yellowing. In addition, there are two large prints loose in a folder: a landscape panorama of the Turgen Mountains ($3^1/_2$ × $11^3/_4$ inches) and a shot of the summit Turgen Peak (9 × 12 inches). Of the 11 photographs from the expedition related to the Turgen Mountains, four matched the photographs that were published in *Unknown Mongolia* (Carruthers 1914a); however, many are unpublished or were taken from a slightly different vantage point. Several of the published photographs were not in the RGS-IBG collection and only exist in Carruthers' book. The photographs were scanned with a large format flatbed scanner at 96 dpi, cropped from the larger pages, rotated to square, and filtered for contrast and brightness. Some photographs with extensive yellowing and stains were restored using black and white filters and content aware fills (Fitzgerald 2010).

The repeated photographs captured in the summer of 2010 were taken with a Nikon D90 digital camera mounted on a mini tripod. The body has a 12.3 megapixel sensor that writes RAW 4288 × 2848 pixel files at 240 dpi to SD digital media cards. All photographs were shot in both RAW NEF and jpg formats using a Nikon 18–105 mm f/3.5–5.6 lens. The photographs were bracketed in ± 1/3 stop increments to ensure proper exposure in the variable lighting conditions of the mountains. Initial processing of the RAW files was accomplished in Adobe Lightroom 2, where all photographs were archived, sorted, and tonally adjusted based on a preset calibrated camera profile. Of the 11 scanned photographs from the RGS-IBG, eight photo points were able to be located in the field and recaptured.

GPS tracks and waypoints digitised from the 1910 Carruthers map were used to approximate the original photo points. Hand written clues in the original captions assisted in identifying many of the photo points. Utilising a copy of the Carruthers map and a handheld Garmin 60CSx GPS, the general location of a point was approached on foot until views matching the original photograph could be aligned by hand. At the assumed photo point, the location was further refined using parallax assessment of ridgeline intersections, perspective alignments, and location of foreground features (Hall 2001; Rogers *et al*. 1984). Once the photo point was accepted, the tripod was set up and re-imaging conducted. A GPS waypoint was taken and its name, positional accuracy, azimuth of shot, date and time were recorded along with any comments concerning the physical setting of the location. In most cases, a series of handheld overlapping shots was taken by rotating 360° on the point. This was done to document the area and facilitate the stitching of individual photographs into panoramas of the entire landscape. As the days progressed, establishing one point often led directly to finding the next, settling into the footsteps of the historic expedition. Figure 2 displays the core study area at the head of the Turgen Valley and the locations of the photos points, along with the route and camps of the 2010 expedition; Table 3 lists the photo points of the repeat pairs and various information including coordinates.

Post-processing of repeated photographs

The scans of the original Carruthers photographs were loaded into Photoshop CS5 software and processed as previously mentioned. The individual scenes were resampled and saved as 300 dpi .tif files. Each 1910 scene was then compared with the bracket of repeated photographs taken in the summer of 2010. A match for each photo point was selected from the library in Lightroom, processed, and then saved as a 300 dpi .tif. Each set of paired repeats was then placed on a separate layer in Photoshop with the 2010 photographs on top of their original paired 1910 photographs, and set to 75% transparency. The 2010 photograph was then positioned and resized until the best fit was achieved. The photographs were not distorted, only resized and aligned after methods outlined by Webb *et al*. (2010). A transparency mask was applied on another layer which allows the 2010 and the 1910 photographs to fade into each other on any axis set in the mask. Visual assessment of the mask overlays indicated a high degree of alignment between the paired repeats. Three paired repeats were then labelled with letters corresponding to areas of noticeable change between the photographs. Number labels were applied to features that exhibit little or virtually no change, similar to the techniques used in

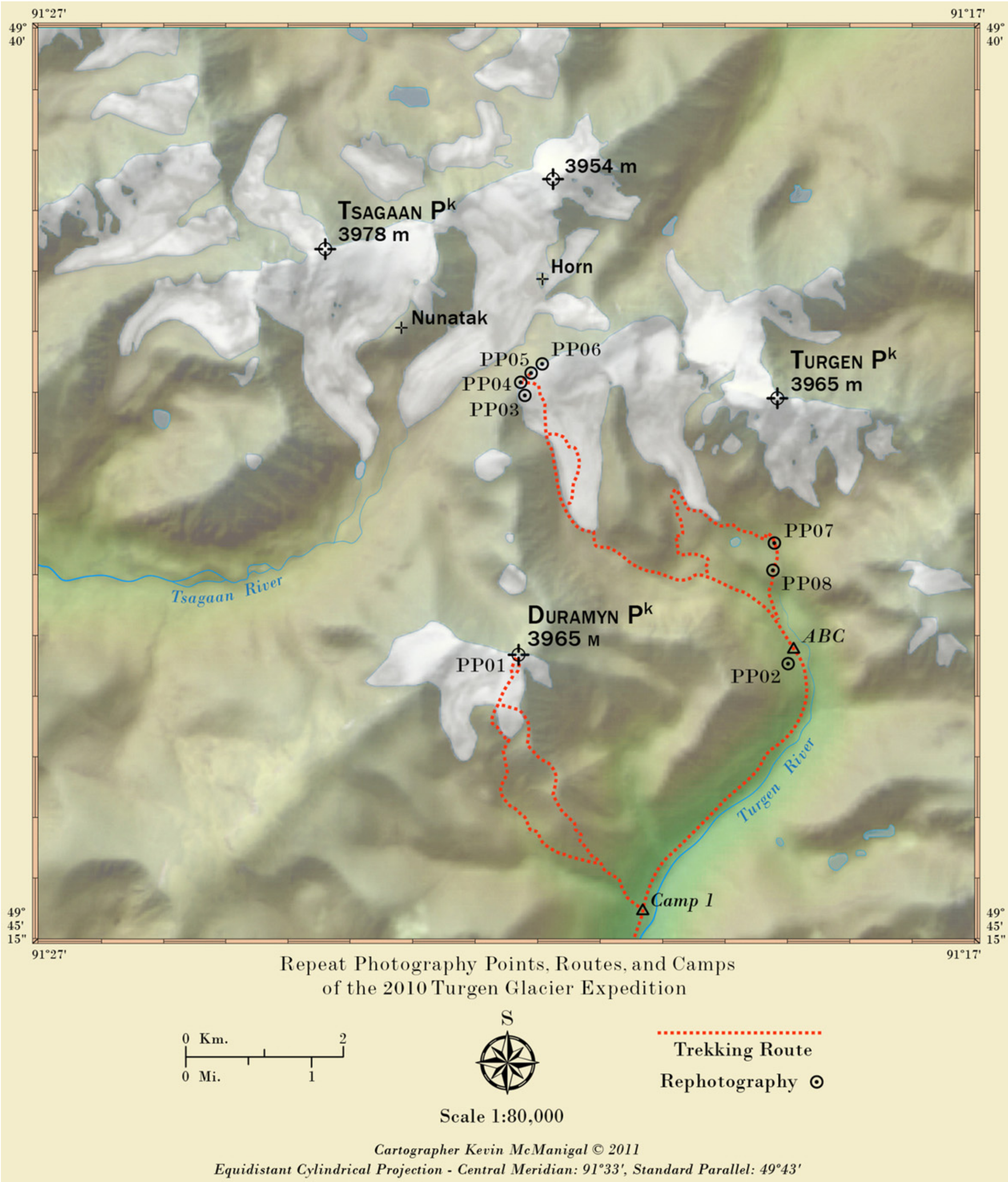


Figure 2 Map of the 2010 core study area in the Turgen Mountains showing locations of photo points (PP), routes, and camps

the Desert Laboratory Repeat Photography Collection (Webb 2007). This labelling for qualitative analysis was applied to photographs from photo points PP01, PP05 and PP06.

Pixel analysis

Previous studies have attempted various techniques to quantify change between pairs of oblique photographs

Table 3 Locations of 2010 repeat photography points

Photo point	Location	Elevation (m)	2010 Azimuth	RGS-IBG photo call no.	Original caption	Original date	Modern date	Point coordinates
PP01	Duramyn Peak	3750	212°	F039/0126	Panorama of the main peaks of the Kundelun [Turgen]	13–19 August 1910	13 July 2010, 15:32	49° 44′ 17.97″ N 91° 21′ 52.06″ E
PP02	Slope above Advanced Base Camp	2659	173°	F039/0119	Mt. Kundelun [Turgen] (13,000 ft) showing the Great Ice Cap and the terminal glacial moraine	13–19 August 1910	14 July 2010, 17:15	49° 44′ 21.57″ N 91° 19′ 00.92″ E
PP03	High slope on East Turgen Glacier	3482	273°	X0738/024743	Peak Kundelun [Turgen] in the Turgun Highlands	13–19 August 1910	15 July 2010, 14:05	49° 42′ 26.14″ N 91° 21′ 51.72″ E
PP04	Col above East Turgen Glacier	3479	79°	F039/0120	Two glaciers descending from the Turgen [Tsagaan] Peak [. . .], each between 2 & 3 miles long	13–19 August 1910	15 July 2010, 13:58	49° 42′ 25.19″ N 91° 21′ 50.78″ E
PP05	Col above East Turgen Glacier	3478	209°	F039/0125	Mount Kundelun [Unnamed Horn]	13–19 August 1910	15 July 2010, 14:18	49° 42′ 23.75″ N 91° 21′ 50.82″ E
PP06	Col above East Turgen Glacier	3501	92°	F039/0124	Mount Kundelun [Tsagaan]	13–19 August 1910	15 July 2010, 14:44	49° 42′ 22.18″ N 91° 21′ 44.17″ E
PP07	S. moraine of West Turgen Glacier	2808	96°	F039/0121	Inside moraine of the eastern [western] Kundelun [Turgen] glacier showing the debris	13–19 August 1910	16 July 2010, 14:08	49° 43′ 32.13″ N 91° 19′ 09.68″ E
PP08	In moraine of West Turgen Glacier	2755	172°	F039/0118	Mt. Kundelun [Turgen] (13 000 ft) from inside the western glacier	13–19 August 1910	16 July 2010, 14:31	49° 43′ 43.27″ N 91° 19′ 10.50″ E

All 1910 photographs by D A Carruthers or M P Price (credit not specified), all 2010 photographs by K G McManigal

(Aschenwald *et al*. 2001; Munroe 2003; Roush *et al*. 2007). However, in this study such techniques were impractical due to the nature of the photographic pairs. To quantify relative change in glacial cover, first the exposed ice on each paired photograph was digitised with Adobe Illustrator software to construct pure bi-tonal slides where white polygons represent ice, and black equals no ice. The 'no ice' polygons included all vegetation, moraines, rocks and sky. In a second step, the pairs were analysed individually in Pixcavator software (version 2007), where the program delineated the contours of the white and black polygons. By comparing these measures for paired photographs, changes in relative ice cover were assessed. Three paired photographs (PP02, PP03, PP08) showing Turgen ice cap, but taken from differing viewpoints, were processed in this way. The percent of relative change in the three pairs was averaged to estimate the total change in ice cover on the Turgen summit.

Multi-data integrative analysis

The relationship between repeat oblique photography and topographic maps for glacial ablation studies has thus far been limited to locating the photo points on the maps (Roush *et al*. 2007; Fagre 2010). The delineation of changes in glacial extent from multi-temporal series maps and satellite imagery is well established; however, inclusion of terrestrial photography in these measurements tends to be problematic since most scenes are wide panoramas taken from high vantage points (Byers 2007; Schmidt and Nüsser 2009). Most of the re-photography in this study falls into this category, but two pairs lend themselves to more accurate measurements.

PP04 Photo point four is located on the col above East Turgen Glacier. The photographs were taken facing northeast and capture two glaciers converging in a medial moraine around a nunatak (Figure S2). The nunatak was identified in the CGIAR DEM and measured using ArcScene 3D software. The DEM was draped with the 2010 Landsat image and rotated on multiple axes to locate the top of the rock formation and the relatively flat surface of the glacier below it. Elevations for the corresponding pixels where subtracted to determine that the height of the nunatak was 300 ± 16 m above the glacier in 2010. The paired photographs of matching resolution were then loaded onto separate layers in Adobe Illustrator software and baseline vectors drawn at the 1910 and 2010 glacier levels. Vertical lines were then drawn perpendicular to the glacier baselines up to the summit of the nunatak. The length of the lines is given by the program in pixels and was used in a simple rule of three. The downwasting of the glacier over the last century at that location was derived from the elevation difference.

PP07 Photo point seven is located on the high sloping western moraine of West Turgen Glacier, with the photographs taken facing to the east (Figure S3). The position is directly below the summit seracs of Turgen Peak and may be exposed to calving ice. The 1910 photograph from PP07 was taken perpendicular to the West Turgen Glacier terminus; the 2010 photo point was matched almost exactly with the 1910 position using parallax techniques. A blended hybrid photograph of the 1910 and 2010 photographs was created so that the 1910 terminus could be seen simultaneously with prominent landscape features in the background of the 2010 photograph. Then a vector was drawn from the known location of the photo point, across the historic 1910 terminus, and intersecting with a peak in the distance. The azimuth of this 'terminus vector' was then plotted between the GPS location for PP07 and the background peak visible in the Landsat image from 2010. By measuring the distance between the 1910 terminus vector and the 2010 glacier terminus in the GIS, a century of glacial recession was measured. Also, outlines of the West Turgen Glacier terminus were digitised from the 1970 Soviet Union map and the 1992 Landsat image. The glacial recession between these years was measured for comparison to the repeat photography results.

Results

Glacier mapping

The results from satellite imagery analysis revealed that in 2010 glaciers covered 31.8 km^2 in the Turgen Mountains (Figure S4 and Table 2). The 1910 Carruthers topographic map was not of sufficient accuracy to be used for glacier extent calculations.

Visual qualitative analysis of repeated photographs

PP05 Photo point five is located on the ridge above East Turgen Glacier that forms the divide between the Turgen and Tsagaan watersheds (Figures 2 and S5). The area of label 'A' shows a substantial ablation of ice behind the horn. The glacier has melted down to exposed moraine and appears to no longer flow around the south side of the horn. There is also a significant loss of ice on the slopes of the background peak labelled as 'B' and 'C,' with considerably more exposed rock in the 2010 photograph. Label '1' on the high slopes of the peak looks similar in both photographs; however, the 2010 photograph shows bare ice in this area, indicating that the equilibrium line may have risen high onto the peak over the last century. The slope also looks to be steeper in the 2010 photograph, indicating a loss of volume.

PP06 The photos of point six were taken from a similar location as PP05, only looking towards the east (Figures 2 and S6). The steep glacier in area 'A' has wasted severely in the preceding hundred years and no longer flows into the glacier below it. The snow and ice on the slopes in areas 'B' and 'C' have completely ablated exposing bare rock and moraines. Again, the area of label '1' on the high slopes looks similar between the years, but the ice appears to be bare and steeper in the 2010 photograph, indicating that the ice there has at least begun to recede.

Pixel analysis

PP02, PP03, PP08 The photographs in these pairs all depict main Turgen Peak. The PP02 shots were taken on the slope just east of Advanced Base Camp (ABC), looking south towards the mountain and the terminus moraine of West Turgen Glacier (Figures 2 and S7). The summit ice cap looks unchanged, but the small glacier descending from the cirque on the right has retreated, along with a reduction of ice in the centre frame seracs. The debris-covered ice in the centre of the moraine has also completely ablated. PP08 is located within the moraine of West Turgen Glacier (Figures 2 and S8). The debris-covered ice is completely absent from the moraine in 2010, but the summit appears almost identical in both years. The PP03 photographs were taken from the ridge above East Turgen Glacier that forms the divide between the Turgen and Tsagaan watersheds (Figures 2 and S9). There are large sections of slope in the foreground, but only the glacial cap was considered here, which looks to be almost the same between the two years.

The results of the Pixcavator analysis on these photo pairs are shown in Table 4. The changes in ice cover between 1910 and 2010 are almost undetectable by visual evaluation, but the pixel analysis results suggest a slight decrease in ice coverage ranging from –0.29% to –2.36% with an average loss of –1.5% between the three pairs.

Multi-data integrative analysis

PP04 The two glaciers that converge below the rock face and flow north show considerable down-wasting over the 100-year time span (Figure S2). The ice also seems to be thinning more rapidly down slope as evidenced by the trim lines and changing surface angles between the two photographs. The exposed rock above the glacier in 1910 was measured at 228 ± 16 m; subtracted from the 300 ± 16 m height in 2010 the glacier surface at the base of the nunatak has down-wasted 72 ± 16 m in the last century.

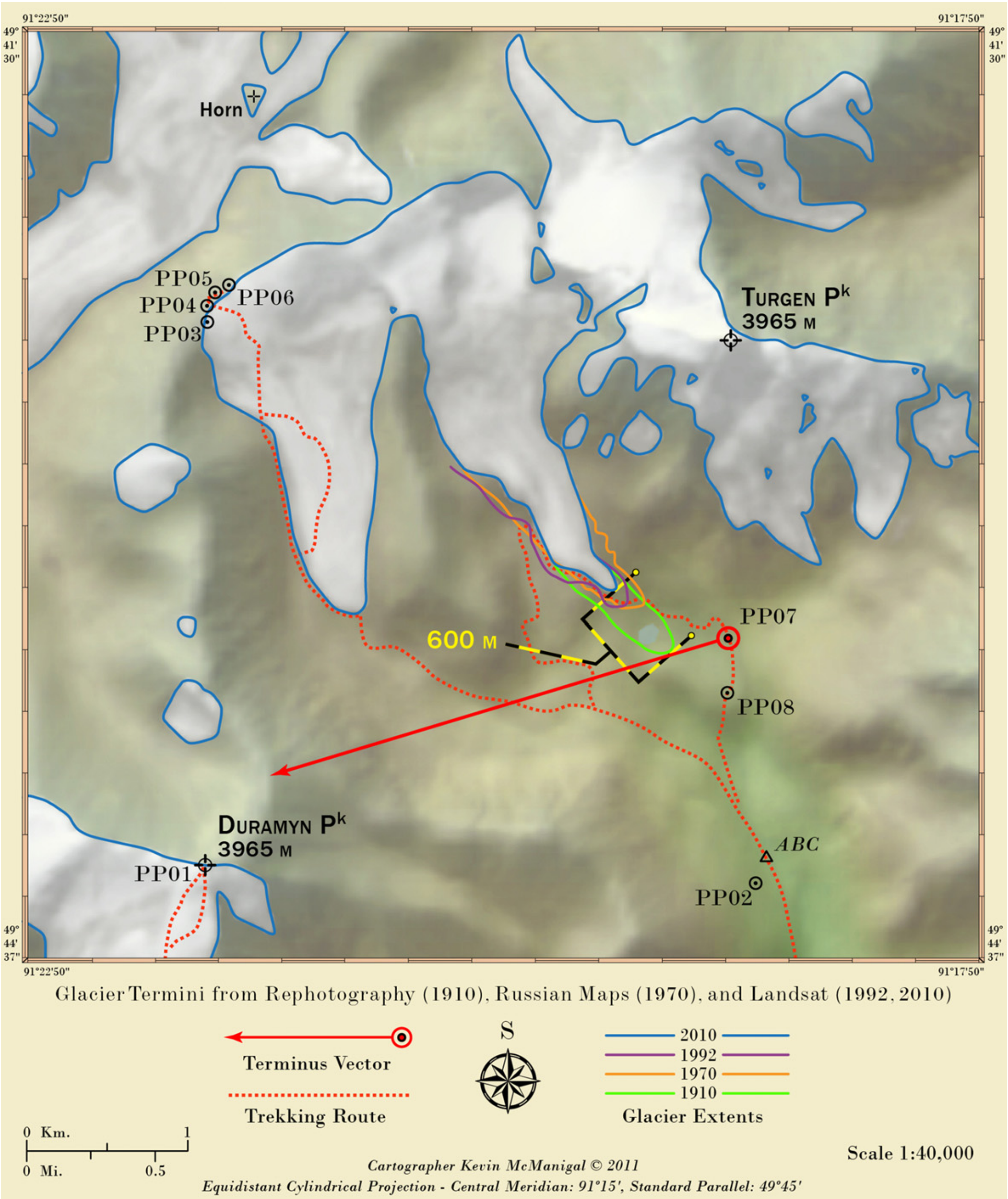
PP07 The paired photographs from this photo point match exactly and display the most extreme glacial recession of the study. Cropped to the 1910 extent, the tongue of West Turgen Glacier is completely absent in the 2010 photograph (Figure S3). The debris-covered ice visible in the 1910 photograph has also completely disappeared, changing the structure of the moraine noticeably. The azimuth of the capture angle plotted over the hybrid Landsat and DEM relief map reveals that the glacier has retreated around 600 m in the last century (Figure 3). Multi-temporal glacier termini locations are also plotted on the map from the 1970 Soviet Union topographic sheets, as well as the Landsat images from 1992 and 2010. An estimated frontal lobe for West Turgen Glacier in 1910 was extrapolated from the known terminus, the shape of the ice in the 1910 photograph, and the curvature of the moraine. Table 5 shows the recession differences between the years and the changing rates of retreat. From 1910 to 1970, West Turgen Glacier retreated 403 m, averaging 6.7 m per year. From 1970 to 1992, the retreat rate appears to have slowed to 3.9 m per year and the glacier receded 87 m. From 1992 and 2010 the retreat rate increased to 6.1 m per year, and the glacier lost 110 m in length. In total, West Turgen Glacier retreated 600 m between 1910 and 2010.

Discussion

In 2010, glaciers covered 31.8 km^2 in the Turgen Mountains, demonstrating a clear glacier recession when compared with the extent of loss documented in existing literature over the last 60 years. However, the glacier extents vary for specific years in the existing literature (Table 1). The ice of the upper glaciated zones above 3500 m appears to have changed very little in the last 100 years. The extent of coverage and thickness of the ice on the Turgen icecap is almost identical between the 1910 and 2010 photographs, but using pixel analysis a loss of –1.5% could be detected. Although small, the differences in ice cover

Table 4 Results from pixel analysis documenting the change in ice area from 1910 to 2010 at Turgen summit

Photo points	Dark pixels (%)	Light pixels (%)	Ice area pixels	Ice perimeter linear pixels	Difference 1910 to 2010 (%)
PP02 _1910	80.31	18.97	54,748	1705	–1.87
PP02 _2010	82.97	17.10	49,295	1461	
PP03 _1910	87.15	12.13	35,417	1306	–2.36
PP03 _2010	89.94	9.77	28,487	1136	
PP08 _1910	97.55	2.45	7150	461	–0.29
PP08 _2010	97.84	2.16	6310	481	



that are undetectable by eye were quantified by this technique. However, the pixel comparison does have several limitations. In the field, the camera locations, azimuth, angle and elevation must match perfectly. In the lab, the resolution and size of the paired photographs also have to be exactly coincident. Slight variations in any parameter will affect the percentages calculated by the software. There may also be error introduced by the manual digitisation of the ice polygons, where visual interpretations have to be made.

Figure 3 The map displays the recession of West Turgen Glacier between 1910 and 2010. Multi-temporal glacier termini locations are plotted from the 1970 Soviet topographic map sheet 1 : 100 000 and the Landsat images from 1992 and 2010. An estimated frontal lobe for West Turgen Glacier in 1910 was extrapolated from the known terminus, the shape of the ice in the 1910 photograph, and the curvature of the moraine. Table 4 shows the recession differences between the years and the changing rates of retreat. From 1910 to 1970, West Turgen Glacier retreated 403 m, averaging 6.7 m per year. Then, the retreat rate appears to have slowed to 3.9 m per year, receding 87 m from 1970 to 1992. Between 1992 and 2010, the retreat rate has increased to 6.1 m per year, losing 110 m in glacier length. In total, West Turgen Glacier retreated 600 m between 1910 and 2001

Table 5 Recession of West Turgen Glacier between 1910 and 2010 from multi-data integrative analysis

	Year						
	1910		1970		1992		2010
Years between images		60		22		18	
Retreat (m) per year		6.7		3.9		6.1	
Retreat (m) per year 1910–2010				5.6			
Retreat (m) between years		403		87		110	
Retreat (m) 1910–1992			490				
Retreat (m) 1910–2010				600			

Changes in volume of ice that ablates directly away from the camera angle would be indiscernible as well. Also, ice or snow surfaces at varying focal lengths should not be analysed together. For example, in the photo pair from PP03, a reduction of the snow along the ridgeline in the foreground would reveal more ice on the summit cap in the background, prejudicing the measurements. Regardless, the technique is a valuable confirmation of visual assessments that inferred slight reductions in the ice cap area.

In contrast to the almost unchanged conditions above 3500 m, the glacier cover and thickness at lower elevations has retracted noticeably. The 490 m of recession between 1910 and 1992 for West Turgen Glacier found in our study is comparable to the 200–500 m of retreat estimated by Lehmkuhl (1998) between 1948 and 1991, although the periods do not match exactly. Kadota and Davaa (2007) described that the Turgen glaciers had lost 19% of their surface area between 1970 and 1990, but remained stagnant thereafter. For West Turgen Glacier our study found a decreased recession rate from 1970 to 1992 compared with 1910 to 1970, followed by an increased recession rate after 1992 to 2010, that is, stagnation after 1990 as described in Kadota and Davaa (2007) could not be found at West Turgen Glacier. As mentioned previously, these inconsistencies probably stem from the differing methodologies and data sources. Rectifying these differences would require careful examination and recreation of the previous studies, which was not attempted here. Likewise, the surface measurements below the nunatak could be used to develop down-wasting estimates for local glacial surfaces at similar elevations; however, estimating total volume loss for entire ice bodies would require advanced modelling beyond the scope of this study.

West and East Turgen glaciers are so close to each other that it seems reasonable to suggest that the recession of East Turgen Glacier would have been comparable to the measured 600 m of retreat for West Turgen Glacier over the same period from 1910 to 2010. This assertion is corroborated by the 1910 termini elevations given by Carruthers (1912 1914a). His measurement of 2895 m (9500 ft) for East Turgen Glacier frontal lobe is 50 m lower than the DEM at a point 600 m down-moraine from the 2010 terminus. Also, there were likely considerable changes to the moraines structures as the debris-covered ice ablated, as shown between the photo pairs (Figure S3).

The measurement of down-wasting of glaciers captured from PP04 is a hybrid of techniques, combing the use of DEMs from Surazakov and Aizen (2006), and the incorporation of oblique imagery referenced to the modelled landscape as demonstrated by Aschenwald *et al*. (2001). The limitations of the hybrid technique lie in the error inherent in the DEM and the ability to perfectly match the repeated photographs to the historical ones in both framing and resolution. Here, considering that the capture parameters of the re-photography appear to match very well, those errors are likely within the ± 16 m of vertical inaccuracy in the DEM. There may be some locational inconsistencies with the surface measurements of the 1910 and 2010 glaciers, but the summit of the nunatak was easy to identify in each photograph. Therefore, the measurement of glacial down-wasting over the last century for this one location can be considered accurate to within ± 16 m.

The glacial recession measurement derived from PP07 is another example of re-photography being integrated with remote sensing data to derive measurements that had previously only been possible with temporal satellite imagery or topographic map comparison (Bishop *et al*. 2007; Schmidt and Nüsser 2009). As the photo capture angle was perpendicular to the glacier terminus and exactly matched to the historical location, it was possible to convert an oblique measurement to a planar distance on the satellite image. This allowed the precise location of the historic glacier terminus to be determined. When evaluated against previous remote sensing research, not only can the total amount of recession be determined for a lengthened time-span, but also the variations in the rate of change over the entire study period. This technique can therefore be utilised to effectively extend the modern satellite archives, theoretically, to the earliest photographic records of glaciers.

While it is not possible to make definitive statements expressing exact quantities of ice loss from visual assessments of photographic pairs without clearly visible glacial margins, there is little doubt that the glaciers of the Turgen Mountains have continued their retreat that was first documented by Carruthers (1912 1914a) a century ago. However, there are clues present in the photographs that portend the current trends. Of interesting note is the thin layer of brown sand covering substantial areas of the glaciers in the 2010 photographs, likely blown in off the Gobi desert to the south. As mentioned by Hewitt (2005), this layer of dust has the opposite effect of a thicker insulating layer of debris, actually enhancing ablation of the ice. The dust layer observed in the field in 2010 was only a few millimetres to a centimetre thick, coating the base of ablating sun cups. Unfortunately, no research was found that addresses the patterns and frequency of dust storms in the study area. Also, the presence of bare ice on high, steep slopes in the 2010 photographs may indicate that the accumulation zones of theses peaks have moved above the physical elevation of some glaciers. When all snow from a previous winter is ablated before summers end, the prospect for a rapidly wasting glacier is high (Knight 1999).

Conclusion

Our repeat photography of photographs from the 1910 Carruthers RGS Expedition to the Turgen Mountains has clearly demonstrated the value of historical expedition material to the modern science of glacier monitoring. Using fieldwork data with data from multi-methods lab analysis allowed comparison of the Carruthers material from 1910 with remotely sensed data, extending the records of glacial change further back in time. While not all of the Carruthers records were useful, some of his photographs in conjunction with latter data provided a comprehensive overview of the glaciers in the Turgen Mountains over the last century.

The standard repeat photography approach of side-by-side comparison detected recognisable reductions of both volume and area in the glaciers. For glacial change monitoring, the location and capture angle of photographs plays a large role in the kind of data that can be derived. Panoramic photographs of summits and glacial landscapes without clearly discernible ice margins are useful for qualitative visual analysis. Photographs taken perpendicular to the terminus or encompassing large stable features which can be located within a DEM are useful for quantitative measurements that yield strong estimates of former glacial structures. Without additional fieldwork, refining integrative techniques can be used to assess existing scientific repeat photography studies of photographs taken perpendicular to the glaciers. Pixel analysis of photo pairs supports the visual evaluation of glacial change, and techniques for extrapolating DEM elevations from oblique repeated photographs help in estimating glacier volume changes.

In 1910, Carruthers reported that all visited glaciers in the Turgen Mountains were in a state of retreat. In our study, a continuing glacial recession was documented between 1910, 1970, 1992 and 2010. In particular, glacial loss occurred at valley glaciers which retreated up to 600 m from 1910 and 2010; above 3500 m the ice cover decreased only slightly. In general, these results match those from the existing literature with the exception that a reported stagnation in glacial coverage after 1990 could not be found; in contrast, here, an increase in the glacier recession rate after 1992 was identified.

From 1961 to 2001, the temperatures – particularly, the winter temperatures – increased in the Altai Mountains much more than those in the entire Mongolia or, for example, the Gobi Desert. At the same time, precipitation, which mostly falls between June and August, changed only insignificantly. Temperatures are predicted to rise by an additional 2–8°C above 2000 temperatures until 2099 for the entire Mongolia. Consequently, in the Mongolian Altai the rise of winter temperatures represents the main responsible parameter for glacial change. Since this warming particularly affects lower elevations, an ongoing recession of valley glaciers in the Altai Mountains must be predicted.

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Note

Figures S1–S9 are included in an online supplement.

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Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site:

Figure S1 Topographic map with the 1910 Carruthers Royal Geographic Society expedition route to the Turgen Mountains
Source: Carruthers (1912)

Figure S2 The repeated photograph from 2010 at photo point PP04 captures two glaciers converging in a medial moraine around a nunatak to the east of East Turgen Glacier. Calculations of the distance between the top of the nunatak and the glacier surface revealed that the glacier down-wasted by around 70 m from 1910 to 2010
Source: photo by Kevin McManigal (July 2010)

Figure S3 Photo point PP07, looking southeast, is located within the moraine of West Turgen Glacier. In this photograph from 2010 the glacier tongue is completely absent, changing the structure of the moraines noticeably
Source: photo by Kevin McManigal (July 2010)

Figure S4 Identification of glaciers in the Turgen Mountains using Landsat TM 5 band ratios. In 2010, glaciers covered 31.8 km^2

Figure S5 Photo point PP05, looking south, is located on the ridge above East Turgen Glacier that forms the divide between the Turgen and Tsagaan watersheds. In this 2010 photograph, the area of label 'A' shows a substantial ablation of ice behind the horn. The glacier has melted down to exposed moraine and appears to no longer flow around the south side of the horn. There is also a significant loss of ice on the slopes of the background peak labelled 'B' and 'C,' with considerably more exposed rock in 2010. Label '1' on the high slopes of the peak looks similar in both photographs; however, the 2010 photograph shows bare ice in this area, indicating that the equilibrium line may have risen high onto the peak over the last century. The slope also looks to be steeper in the 2010 photograph, indicating a loss of volume
Source: photo by Kevin McManigal (July 2010)

Figure S6 Photo point PP06, looking east, is close to PP05 on the ridge above East Turgen Glacier that forms the divide between the Turgen and Tsagaan watersheds. In the 2010 repeat photograph, the steep glacier in area 'A' has wasted severely in the preceding hundred years and no longer flows into the glacier below it. The snow and ice on the slopes in areas 'B' and 'C' have completely ablated exposing bare rock and moraines. Again, the area of label '1' on the high slopes looks similar between the years, but the ice appears to be bare and steeper in the 2010 photograph, indicating that the ice there has at least begun to recede
Source: photo by Kevin McManigal (July 2010)

Figure S7 Photo point PP02 is located on the slope just east of Advanced Base Camp, looking south towards Turgen Peak and the end moraine of West Turgen Glacier to the left. In this 2010 photograph, the summit ice cap looks unchanged compared with 1910, but the small glacier descending from the cirque on the right has retreated, along with a reduction of ice in the centre frame seracs. The debris-covered ice in the centre of the moraine has also completely ablated
Source: photo by Kevin McManigal (July 2010)

Figure S8 Photo point PP08, looking south at Turgen Peak, is located within the moraine of West Turgen Glacier. In this photograph from 2010, the debris-covered ice is completely absent from the moraine in 2010, but the summit appears almost identical compared with 1910
Source: photo by Kevin McManigal (July 2010)

Figure S9 Photo point PP03, looking west at Turgen Peak, is located on the ridge above East Turgen Glacier that forms the divide between the Turgen and Tsagaan watersheds. In the 2010 photograph, the glacial cap looks to be almost the same as in 1910. The ice on the slope in the foreground is covered with dust only in the 2010 photograph
Source: photo by Kevin McManigal (July 2010)