Accelerated loss of alpine glaciers in the Kodar Mountains, south-eastern Siberia

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Abstract:

The recession of mountain glaciers around the world has been linked to anthropogenic climate change and small glaciers (e.g. <2 km^2) are thought to be particularly vulnerable, with reports of their disappearance from several regions. However, the response of small glaciers to climate change can be modulated by non-climatic factors such as topography and debris cover and there remain a number of regions where their recent change has evaded scrutiny. This paper presents results of the first multi-year remote sensing survey of glaciers in the Kodar Mountains, the only glaciers in SE Siberia, which we compare to previous glacier inventories from this continental setting that reported total glacier areas of 18.8 km^2 in ca. 1963 (12.6 km^2 of exposed ice) and 15.5 km^2 in 1974 (12 km^2 of exposed ice). Mapping their debris-covered termini is difficult but delineation of debris-free ice on Landsat imagery reveals 34 glaciers with a total area of 11.72 ±0.72 km^2 in 1995, followed by a reduction to 9.53 ±0.29 km^2 in 2001 and 7.01 ±0.23 km^2 in

2010. This represents a ~44% decrease in exposed glacier ice between ca. 1963 and 2010, but with 40% lost since 1995 and with individual glaciers losing as much as 93% of their exposed ice. Thus, although continental glaciers are generally thought to be less sensitive than their maritime counterparts, a recent acceleration in shrinkage of exposed ice has taken place and we note its coincidence with a strong summer warming trend in the region initiated at the start of the 1980s. Whilst smaller and shorter glaciers have, proportionally, tended to shrink more rapidly, we find no statistically significant relationship between shrinkage and elevation characteristics, aspect or solar radiation. This is probably due to the small sample size, limited elevation range, and topographic setting of the glaciers in deep valleys-heads. Furthermore, many of the glaciers possess debris-covered termini and it is likely that the ablation of buried ice is lagging the shrinkage of exposed ice, such that a growth in the proportion of debris cover is occurring, as observed elsewhere. If recent trends continue, we hypothesise that glaciers could evolve into a type of rock glacier within the next few decades, introducing additional complexity in their response and delaying their potential demise.

1. Introduction

The Intergovernmental Panel on Climate Change concluded that warming of the climate system is unequivocal and that the world's glaciers are losing mass in response to both atmospheric and oceanic warming (IPCC, 2007). This loss has resulted in sea level rise and the majority of the recent contribution from the cryosphere is derived from mountain glaciers and ice caps (~60% between 1996 and 2006), rather than the large ice sheets in Greenland and Antarctica (Meier *et al.,* 2007; although see Rignot *et al.*, 2011). Indeed, estimates of glacier mass balance from outside Greenland and Antarctica have become progressively more negative since the 1970s (Dyurgerov and Meier, 2000; Kaser *et al*., 2006; Zemp, *et al*., 2009) and their contribution to sea level rise is likely to continue to increase in the 21st century, despite uncertainties (Meier *et al*., 2007; Pfeffer *et al*., 2008; Bahr *et al*., 2009; Radić and Hock, 2011).

The response of a glacier to a change in climate is complex but small glaciers (e.g. <2 km^2) will tend to respond more rapidly to a given change in temperature and/or precipitation compared to larger glaciers (Meier, 1984; Oerlemans *et al*., 1998; Granshaw and Fountain, 2006). As such, they are important indicators of climate change and their existence is threatened in some regions (e.g. Ramírez *et al.,* 2001; Zemp *et al*., 2006; Thompson *et al*., 2011). Indeed, glacier disappearance has been reported in several areas, e.g. Canadian Rocky Mountains (Tennant *et al*., 2012), North Cascade Range, USA (Granshaw and Fountain, 2006), Ak-Shiryak Range, Central Asia (Khromova *et al*., 2003), Terskey-Alatoo, Tien Shan (Kutuzov and Shahgedanova, 2009) and Italian-French Alps (Federici and Pappalardo, 2010). Whilst these observations and theoretical considerations (Oerlemans *et al.,* 1998) suggest that small glaciers are most vulnerable, other work has reported only minimal changes in their extent in recent years (e.g. DeBeer and Sharp, 2007; 2009; Hoffman *et al.,* 2007) and this has been attributed to favourable topographic settings and/or locations at relatively high elevations (Kuhn, 1993; DeBeer and Sharp, 2009; Kutuzov and Shahgedanova, 2009). It is important, therefore, to investigate the recent response of small glaciers from a range of climatic regimes and topographic settings, and to extend observations to areas where change has not been investigated (cf. Dyurgerov and Meier, 2000; Ohmura, 2009). One such area is the Kodar Mountains in south-eastern Siberia.

The first study on glaciers in the Kodar Mountains was by Preobrazhenskiy (1960) and his observations were updated for the Russian Catalogue of Glaciers (Katalog Lednikov, Novikova and Grinberg, 1972; here on referred to as 'KL'), which was subsequently transferred into the World Glacier Inventory (WGI) without being updated (National Snow and Ice Data Center, 1999: http://nsidc.org/data/glacier_inventory/). Since then, the region has attracted very little attention. This may reflect the remoteness of the Kodar Mountains and the relatively small number of glaciers (30 according to the KL/WGI), but the region is potentially important for a number of reasons. First, there has been no analysis of multi-year changes in glacier extent and it is unknown whether glaciers in this region mirror the recent glacier recession seen in other parts of Siberia (e.g. Ananicheva *et al*., 2005; 2006; Surazakov *et al*., 2007; Gurney *et al*., 2008). Second, Kodar glaciers are located in an extreme continental climate. Oerlemans and Fortuin (1992) suggested that the climatic sensitivity of glaciers can vary over at least one order of magnitude, depending on precipitation, with continental glaciers less sensitive than those in more maritime regions (cf. Meier, 1984; Braithwaite *et al.*, 2003; Anderson and Mackintosh, 2012). However, continental glaciers are generally under-reported in the literature and Kodar glaciers fill an important gap in this regard. Third, supporting the previous point, Solomina (2000) suggested that glaciers in the Kodar Mountains had shown the least recession from their 'Little Ice Age' (LIA) moraines to the 1980s, compared to glaciers in other regions in northern Eurasia. Thus, there is a clear requirement for an up-to-date analysis of recent change and the objectives of this paper are to: (i) construct an updated glacier inventory for the region, (ii) provide the first multi-year remote sensing survey of recent changes, and (iii) compare recent changes to earlier glacier inventories and explore possible controls on glacier change (both climatic and topographic).

2. Previous Work on Glaciers in the Kodar Mountains

2.1. Topography and climate

The Kodar Mountains are located in south-eastern Siberia between 56°45’ and 57°15’ N, and 117° and 118° E, bordered by the Vitim and Olyokma tributaries of the Lena River (Fig. 1). Glaciers are located around the upper reaches of the Sygykta River (a tributary of the Vitim), approximately 500 km northeast of Lake Baikal and 1,100 km west of the Sea of Okhotsk. With the exception of some tropical glaciers, they are the most isolated small group of glaciers on Earth: over 1200 km from any other known glaciers (e.g. East Sayan, Orulgan, and Suntar-Khayata Mountains).

The topography is characterised by narrow, deep valleys with local relief in excess of 1,000 m (Fig. 1b). These are the highest mountains in Transbaikalia – the highest peak, Baikal Amur Magistral (‘Pik BAM’) reaches 3,072 m a.s.l. - and their altitude allows glaciers to develop, which is in contrast to other mountain systems at the same latitudes east of Lake Baikal (Fig. 1). The climate is extreme continental and the Siberian high is a dominant feature between November and March, resulting in very low temperatures and precipitation (Panagiotopoulos *et al*., 2005). Meteorological measurements in the 1960s reported annual precipitation totals of 850-1000 mm at 2,500 m a.s.l., which was probably just above most equilibrium line altitudes at the time, with 50% of this falling as snow (Novikova and Grinberg, 1972). Snow can occur at any time throughout the year but 80% falls in late spring (May/June) and early autumn (September) (Novikova and Grinberg, 1972; Solomina and Filatov, 1998).

Glaciers have developed in an area ca. 25 x 25 km (Fig. 1b) and, according to the KL/WGI data from 1959-1963, they range in area from 0.2 to 1.4 km^2 and in length from 0.4 to 2.1 km, with gradients averaging 14.6°. Whilst glaciers favour a northerly aspect (vector mean 023°), Evans

(2006) noted that Kodar glaciers facing NNW tend to reach lower altitudes, which is in contrast to the N or NE tendency for most of the regions in his global analysis. This may relate to secondary snow transport, i.e. wind transport and avalanche activity. Indeed, Solomina and Filatov (1998) found a pronounced increase in easterly winds during the three months with greatest snowfall (May, June, September), which might favour accumulation on westward-facing lee slopes, despite westerly winds dominating on an annual basis. Re-freezing of summer meltwater onto the glacier surface (superimposed ice formation) is an important component of glacier mass balance (Preobrazhenskiy, 1960; Sheinkman, 2011), adding further complexity to the measurement and modelling of their present and future mass balance (Shahgedanova *et al*., 2011).

Evidence for formerly more extensive glaciations is present and includes large terminal moraines, palaeo-shorelines and deltas of glacially impounded lakes (Shahgedanova *et al*., 2002; Margold and Jansson, 2011; Sheinkman, 2011). The largest – Glacial Lake Vitim – may have been associated with a major outburst flood (Margold *et al*., 2011).

2.2. Previous glacier inventories

The first glacier inventory was published by Preobrazhenskiy (1960) and included 31 glaciers with a total area of 15 km^2 (Fig. 2). He argued that they were not “dead relicts” but existed “in natural conditions which provide for their normal development” (Preobrazhenskiy, 1960, p. 70). A similar surface area of glacier coverage was reported by Avsiuk and Kotlyakov (1967) who estimated a total ice volume of around 1.2 km^3 based on an assumed average ice thickness of 80 m, which is probably an overestimate given the size of these glaciers.

The KL/WGI document only 30 glaciers because they exclude Preobrazhenskiy's (1960) glacier number 7, which may not exist, but the total glacier area is reported at 18.8 km^2, with 4.8 km^2 debris-covered (25.5%). Since then, two further studies have reported glacier areas: Plastinin and Plyusnin (1979; see also Plastinin, 1998) found 39 glaciers with a total area of 15.5 km^2 in 1974 (with 23% of the total area debris-covered); and Osipov (2010) reported 42 glaciers in 2001 covering 11.9 km^2 (with 40% of the total area debris-covered). Apart from reductions in glacier area over time and the possibility that larger glaciers split into smaller glaciers (although this is unlikely for these small cirque/valley glaciers), the discrepancy between different authors probably results from: (i), different source data, e.g. fieldwork, imagery of different resolution, and (ii), different criteria for defining and identifying debris-covered and/or very small glaciers, rock glaciers, icings (frozen river/lake or spring water) and snow patches.

2.3. Historical glacier extent

There are no dates available from terminal moraines associated with the most recent sustained glacial advance(s) in the Kodar Mountains (Fig. 3). However, dendrochronology suggests reduced tree growth at the tree line during the second half of the 17th century and this probably coincided with glacier advance (Solomina and Filatov, 1998). Using the same technique, other possible and more recent advances were dated at 1728-1743 and 1763-1773 (Lovelius, 1979), although it is not clear whether these dates correspond to the LIA maxima in the region. Preobrazhenskiy (1960) also described these major moraines, which he noted as having an asymmetric profile with steep ice-distal slopes ranging from 20-130 m high. He also reported that most glaciers have retreated tens to a few hundred metres from these moraines but that some glaciers are still close to them. For example, glacier number 5 (SU5D17201005, Sygyktinskiy:

numbers from here on refer to those in the KL/WGI) was described as within a few tens of metres of its major terminal moraine in the 1960s (Shtyurmer, 1962), whereas glacier number 21 (Yablonskiy) had receded approximately 300 m from a similar moraine complex (Laptev and Lukashev, 1962).

Supporting these observations, Solomina (2000) compared the length change of glaciers from their LIA position to the mid-20th century for a number of different regions in northern Eurasia (Caucasus, Pamir-Alay, Tien Shan, Altai, Kodar, Suntar-Khayata, Cherskiy, Koryakskoye Nagorye, Kamchatka). Compared to other areas, a sample (n = 23) of most glaciers in the Kodar mountains had retreated the least distance by the 1960s (mean = 130 m; range = 0-500 m) and she suggested that small, cold glaciers in the severe continental climate of south-eastern Siberia appear to be much less variable than glaciers elsewhere in northern Eurasia that have higher mass-energy transfers. Indeed, the first direct measurements of ice flow velocity were conducted in 2007-2008 on the Azarova Glacier (Fig. 3) and revealed relatively slow velocities of between 2.4 and 3.9 m a^{-1} for different sections of the glacier (Shahgedanova *et al.*, 2011).

3. Methods

3.1. Data sources

Glaciers were mapped mainly from three Landsat satellite images acquired on 17 July 1995 (Thematic Mapper (TM) path 126, row 020), 11 July 2001 (Enhanced Thematic Mapper plus (ETM+) path 126, row 020) and 27 July 2010 (ETM+ path 127, 020). The two westernmost glaciers (numbers 29 and 30) were not covered by the 2001 scene and their outlines were taken from an adjacent image from path 128, row 020 on 13th August 2002.

Images were obtained from the United States Geological Survey GLOVIS website (http://glovis.usgs.gov/) where they are provided pre-processed with Standard Terrain Correction (Level 1T). This includes systematic radiometric and geometric calibration by incorporating ground control points and using a Digital Elevation Model (DEM), resulting in a horizontal positional accuracy of ±30 m or less with a 90% confidence level. Images were obtained orthorectified to Universal Transverse Mercator, Zone 50 (Spheroid and Datum: WGS 84). Image (pixel) resolution is 28.5 m (15 m for the panchromatic band 8 of the ETM sensor) and care was taken to select largely cloud-free images with minimal snow cover from the short summer ablation period (July-August). Note, however, that perennial snow-patches and icings are numerous (cf. Sheinkman, 2011) and introduce uncertainty (discussed in section 3.3).

In May 2003, the Scan Line Corrector (SLC) failed on Landsat 7, resulting in data loss along scan lines on our 2010 image. However, the SLC-off effects are most pronounced along the edge of each scene and, because the study region lies near the centre of path 127, row 30, the problem only affected five of the mapped glaciers in 2010. Moreover, the systematic nature of the 'striping' effect did not inhibit their mapping.

We also searched for cloud-free declassified reconnaissance imagery from 1960s and 1970s using the USGS Earth Explorer website (http://earthexplorer.usgs.gov/) and found two scenes from the CORONA camera that were acquired on 12 July 1964 (DS1008-1021DA088 and DS1008-1021DF082), i.e. around the time that the KL data were compiled. These allowed visual inspection of some glaciers at a very high resolution (3-4 m), but the scenes were difficult to orthorectify to extract accurate measurements.

In order to explore potential controls on glacier change, we extracted elevation data from the ASTER Global DEM version 2 from the United States Geological Survey Land Processes Distributed Archive Center (LP DAAC: http://gdex.cr.usgs.gov/gdex/). This has estimated accuracies of 20 metres for vertical data and 30 meters for horizontal data, both at 95% confidence. Elevation data were extracted from the ASTER GDEM by overlaying glacier outlines and using the zonal statistics tool in ArcGIS v. 9.3 to extract the minimum and maximum elevation data and the overall gradient. We also used the 'Solar Radiation' tool in ArcGIS and the ASTER GDEM to produce a surface of annual potential incoming solar radiation (watt hours per square meter) over each glacier, again using the zonal statistics function.

To compare glacier change to possible climate forcing, a time series of air temperature and precipitation from the Chara meteorological station (56.92° N; 118.37° E; 711 m a.s.l.: location shown on Fig. 1) were used to evaluate variations in regional climate. This is the only station close to the study area with a continuous long-term record. Air temperature and precipitation time series start in 1938 and 1951, respectively. The starting year for precipitation measurements was taken as 1960 to avoid potential observational biases due to the introduction of Tretyakov rain gauge, which replaced the Nipher gauge in the 1950s (Yang and Ohata, 2000). Additionally, we used NCEP/NCAR (Kalnay *et al*., 1996) and ERA Interim (Dee *et al*., 2011) data for precipitation and air temperature at 2 m averaged over the region extending between 56.5-57.5N and 117-118.5E.

3.2. Glacier delineation

Delineation of glaciers in the Kodar Mountains from remote sensing is particularly challenging due to: (i) their small size (<1.4 km^2); (ii) the presence of supraglacial debris cover; (iii), the presence of perennial snow patches and icings; and (iv), shadows resulting from their location in deep valley-heads (cirques). Initially, we digitised the outline of both debris-covered and debris-free ice and tested a number of well-known automated/semi-automated techniques to extract glacier outlines (Fig. 4). These techniques are especially useful for large sample sizes and/or large glaciers where manual delineation would prove extremely time-consuming, but their value can be limited by areas of glacier ice cast in shadow and, more severely, by supraglacial debris (see Pellikka and Rees, 2010; Paul *et al*., 2002; Gjermundsen *et al*., 2011). We gained little confidence that any of the automated/semi-automated methods could accurately map the terminus of debris-covered glaciers across the three images (cf. Gjermundsen *et al*., 2011). Even for debris-free ice, results were mixed, although some techniques clearly performed better than others (Fig. 4).

Given these considerations, we decided to use on-screen manual digitising techniques to map the relatively small number of glaciers and we restricted our mapping to areas of debris-free ice (cf. De Beer and Sharp, 2009). We experimented with a number of different band combinations and found a false-colour composite image of bands 5, 4, 3 most useful (Fig. 4a), on a pan-sharpened (15 m resolution) ETM+ image (Paul *et al*., 2003; Stokes *et al*., 2006; 2007). This band combination produces a helpful contrast between debris-free ice (blue, with snow in the accumulation area appearing turquoise), supraglacial debris (deep purple), adjacent debris and bare rock (pink) and vegetated surfaces (bright green). Mapping was undertaken in ERDAS Imagine 2010™ and the area and perimeter of each polygon shapefile were derived from the attribute table. Tabulated areas for each measurement year (1995, 2001, 2010) were compared to determine changes in the area of debris-free ice. An approximation of glacier length was also obtained from measuring the distance along an assumed flow-line from the upper-most glacier extent to the lower-most debris-free extent.

We excluded snow-patches and icings present on the imagery. Thorough inspection of all imagery confirmed the presence of exposed glacier ice in all small glaciers, thereby distinguishing them from snow patches. In addition, many snow-patches exhibit an irregular and variable geometry with intermittent rock outcrops, and often markedly change shape between different time-steps (see also De Beer and Sharp, 2007). Finally, elevation data from the ASTER GDEM helped exclude larger icings present at much lower elevations than are required for glacier survival in this region.

3.3. Remote sensing error assessment

Errors are introduced by the resolution of the satellite image in terms of what can be seen, and the contrast between the glacier and adjacent terrain (Hall *et al.,* 2003; Burgess and Sharp, 2004; De Beer and Sharp, 2007). For debris-free glacier ice that is not obscured by cloud or shadow, De Beer and Sharp (2007) suggested that the line placement uncertainty is unlikely to be larger than the resolution of the imagery, i.e. ±28.5 m for the 1995 image and ±15 m for the pan-sharpened 2001 and 2010 imagery. Thus, for Azarova Glacier (number 20; Fig. 3, 4), the debris-free area in 2010 is digitised at 527,792 m^2, with a perimeter of 4,358 m. The measurement error = the polygon perimeter (4,358 m) x pixel resolution (15 m) = 65,370 m^2, i.e. the total area = 0.53 ± 0.07 km^2 (i.e. ±13%). Additionally, the Azarova Glacier has recently been measured in the field by a photo-theodolite survey (Shahgedanova *et al*., 2011). That survey recorded a debris free area of 0.56 km^2 in 2007, which is entirely consistent with our 2010 value. We further evaluated this error term by independently re-digitising the same glacier (number 27) ten times, varying the scale and the band combinations. The difference between the minimum and maximum areas was only 0.01 km^2 for a glacier initially measured at 0.15 km^2 i.e. 6-7% of the total area. This suggests that our error term for the 2001 and 2010 imagery is probably conservative.

In contrast, the TM scene from 17th July 1995 contained more cloud and snow than the other scenes. Following Burgess and Sharp (2004) and De Beer and Sharp (2007), we increased the line placement error to 90 m to account for segments of the perimeter partly obscured by cloud or late-lying snow, i.e. total error = (length of perimeter not obscured x 28.5 m) + (length of perimeter obscured by cloud/snow x 90 m). The net result is that there is greater uncertainty for the 1995 data.

4. Results

4.1. A new glacier inventory for the Kodar Mountains

An important outcome of this study is an up-to-date glacier inventory that can be compared to previous ones. We identified all of the glaciers on Preobrazhenskiy's (1960) map, apart from glacier number 7 (below centre on Fig. 2), which was also excluded from the KL inventory (Novikova and Grinberg, 1972) and the WGI. Either this glacier disappeared soon after Preobrazhenskiy's (1960) observations or it was misidentified. We also note that the glacier labelled '?' on his original map (far left on Fig. 2) is not identifiable. This glacier is also omitted from the KL/WGI inventory.

Fig. 5 is a location map of our new inventory from 2010 and Table 1 details the areas of exposed ice in 1995, 2001 and 2010, alongside data from the KL/WGI. The total area of exposed ice in 2010 is 7.01 ±0.23 km^2, which is almost half the value of exposed ice given in the KL/WGI inventory (12.60 km^2) based on data obtained between 1959 and 1963 (Novikova and Grinberg, 1972).

Our inventory includes four additional glaciers that are not included in either Preobrazhenskiy's (1960) or the KL/WGI inventories, located ~5 kilometres north-west of the northernmost glacier in those inventories. They are included in two more recent studies (Plastinin and Plyusnin, 1979; Plastinin, 1998; Osipov, 2010) and appear on Plastinin and Plyusnin's (1979) map as glaciers 33-36. It is not clear why these four glaciers were excluded from the KL/WGI inventories: their size is similar to that of other glaciers in the study area and they possess identifiable terminal moraines that demarcate historical limits down-valley (Fig. 5b). Here, we follow Plastinin and Plyusnin's (1979) numbering scheme (33, 34, 35 and 36, from west to east) and recommend they be ingested into the WGI with the appropriate prefix (SUD172010…). We also acknowledge that there may be 5 additional glaciers within the region because Osipov (2010) cited 41. Unfortunately, Osipov (2010) did not include a map and so we are unable to verify their location. However, if they exist, they must be very small to avoid detection on our imagery (<0.01 km^2: Paul *et al*., 2002) and are unlikely to greatly influence calculations of the total area of exposed ice.

4.2. Change in exposed ice area (1995-2001-2010)

The total area of exposed ice has progressively decreased from 11.72 (± 0.72) km^2 in 1995 to 9.53 (± 0.29) km^2 in 2001 and 7.01 (± 0.23) km^2 in 2010 (Table 1; e.g. Fig. 6). The size distribution of the total population of glaciers (n = 34) at each of these three time-steps demonstrates a clear shrinkage across all size ranges and a resultant decrease in the mean glacier size from 0.34 km^2 in 1995 to 0.21 km^2 in 2010 (Fig. 7). Overall, the mean percentage of exposed ice area lost between 1995 and 2010 was 45% (median = 41%) with the maximum relative shrinkage recorded by one of the smallest glaciers, number 33, which lost 93% of its original area (Fig. 8). The minimum retreat of debris-free ice was experienced by one of the largest glaciers, number 26 (Sygyktinskiy), which only lost 14% of its exposed ice area since 1995. Earlier work suggested that this glacier remained close to its LIA limits in the 1960s (Shtyurmer, 1962).

To explore potential controls on the magnitude of shrinkage experienced by different glaciers, we compared the areal loss of debris-free ice from 1995 to 2010 (both km^2 and percentage) against the original area and length of the exposed ice area in 1995 (Fig. 9). Whilst there is a statistically significant relationship ($r^2 = 0.56$; $p < 0.0001$) for larger glaciers to lose more exposed ice (Fig. 9a; cf. Granshaw and Fountain, 2006; Stokes *et al*., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009), the relationship is not quite significant when areal loss is expressed as a percentage of the original glacier size ($r^2 = 0.11$; $p = 0.053$) and, in fact, the correlation becomes negative such that smaller glaciers are more likely to lose proportionally more of their area (Fig. 9b).

There is also a significant relationship between glacier length and total area loss from 1995-2010 ($r^2 = 0.31$; $p = 0.0006$: Fig. 9c), indicating that longer glaciers, unsurprisingly, lose more ice in absolute terms. However, when area loss is expressed in percentage terms, the correlation again becomes negative and is weaker but statistically significant ($r^2 = 0.16$; $p = 0.02$: Fig. 9d); indicating that shorter glaciers lost more of their area than longer ones. Note that length, area and area loss are all positively skewed. This can be rectified by logarithmic transformations, which produce similar results and significant relationships for all of these correlations.

Aspect is another potential control on the magnitude of shrinkage and glaciers in the Kodar Mountains have a statistically significant aspect tendency towards NNE (013°; p = <0.05). Glaciers facing SE have receded the most (on average losing 68% of their exposed ice area: Fig. 10) but those facing NW have lost almost as much (61%). However, there are no statistically significant trends with either aspect or annual potential clear sky radiation. We also explored whether elevation influenced the shrinkage of debris-free ice, but found no significant relationships between the percentage of exposed ice lost between 1995 and 2010 and either minimum elevation ($r^2 = 0.04$; p = 0.24), maximum elevation ($r^2 = 0.05$; p = 0.22), or gradient ($r^2 = 0.001$; p = 0.83).

5. Discussion

5.1. Recent changes in exposed glacier extent and comparison to previous inventories

Our survey spanning 15 years reveals a ~40% reduction in the total area of exposed glacier ice from 1995 to 2010 (Table 1). The rate of shrinkage remained relatively steady at 3.11% a^{-1} between 1995 and 2001, and 2.94% a^{-1} between 2001 and 2010 (Table 2). In contrast, a comparison between our data and those reported from previous Russian inventories reveals only minimal recession between 1963 and 1974 (0.43% a^{-1}) and between 1974 and 1995 (0.11% a^{-1}). Thus, retreat rates in the Kodar Mountains appear to have almost tripled after 1995 (3.12% a^{-1} to 2001) before a slight reduction in the rate of retreat between 2001 and 2010 (2.94% a^{-1}) but this remains a much greater rate than for 1963 to 1995. A time series of the total exposed ice area from the different inventories (Fig. 11) illustrates the recent acceleration in shrinkage identified in this study.

We note the discrepancy between our total area in 2001 and that reported by Osipov (2010), whose value of 7.10 km^2 falls outside our error term (Fig. 11). Like us, Osipov (2010) also found marked shrinkage, but because he does not include a map we can only speculate why his value is so much smaller and suggest it results from different source data and/or different criteria for identifying smaller debris-covered glaciers, rock glaciers, icings or snow patches.

Questions have been raised over the reliability of data in the KL (e.g. Bolch, 2007; Grant *et al.*, 2009; Shahgedanova *et al*., 2010), which may have implications for the '1963' data (Fig. 11 and Table 2). We inspected the KL data for each glacier (Table 1) and found that most values appeared consistent but that two glaciers (numbers 13 and 19) were more than double the 1995 value, and one (number 4) was less than half the 1995 value. Given that these are the only obvious discrepancies, we suggest that the total area of exposed ice reported in the KL is reasonably accurate and, moreover, consistent with a later inventory by Plastinin and Plyushin (1979). If anything, we suspect the KL data may be a slight under-estimate of the total area of exposed ice in the early 1960s, especially as it includes fewer glaciers than later inventories. Indeed, inspection of the higher resolution CORONA imagery from 1964 confirms large areas of exposed ice in the 1960s (Fig. 12).

5.2. Potential drivers of glacier recession

Shahgedanova *et al.* (2011) used terrestrial photogrammetry and calculated changes in the surface area, elevation, volume and geodetic mass balance of the Azarova glacier (number 20: on Fig. 2-4). Between 1979 and 2007, the surface area reduced by 20 ± 6.9% and thinned by an average of 20 ± 1.8 m. This resulted from a strongly negative cumulative mass balance of -18 ± 1.6 m w.e. over 28 years. Significantly, Shahgedanova *et al.* (2011) reported that between 1980 and 2007, average summer air temperatures recorded at Chara (56.92° N; 118.37° E; 711 m a.s.l.) increased by 1°C, compared to the 1938-1979 period. Furthermore, the July-August air temperature record displays a strong warming trend of 0.036°C a^{-1} between 1979 and 2007, which they suggest was the main driver of the observed glacier thinning.

In this study, we have updated the Chara records to 2010 and can confirm that warming occurred in all seasons from around the start of the 1980s (Fig. 13). Of particular importance is the time series of air temperature for June-July-August (Fig. 13a) because this spans the short ablation season between approximately the end of June and mid-late August (Novikova and Grinberg, 1972). Note that although Chara is located at an elevation lower than the glaciers in the mountains, its JJA temperature record correlates closely with the NCEP/NCAR and ERA Interim reanalyses data (Fig. 13) which are averaged over the region extending between 56.5-57.5° N and 117-118.5° E, and both of which account for variations in elevation (correlation coefficients are 0.68 and 0.93, respectively, for the overlapping period between 1979 and 2010).

The JJA temperature record at Chara shows a strong increase from ca. 1980, particularly after 1995, which coincides with the observed shrinkage of debris-free ice. Indeed, Fig 14 shows that the 2000-2010 decade was the warmest on record with a mean JJA temperature of 15.2 ^{o}C, exceeding the overall mean from 1938 to 2010 by 1^{o}C. In relation to our intervals of glacier change, air temperature averaged 13.9 °C for the period 1960-1995, but 15 °C for the period

1995-2010. Indeed, the JJA means from 1998, 2001 and 2002, were two standard deviations above the overall record mean. In another warm summer, 2008, mean June temperature was the highest on record, reaching 17.8 °C: a 4.7 °C positive anomaly indicating a very early start to the ablation season.

It is more difficult to assess temporal trends in the accumulation season (September-May) precipitation (shown in Fig. 13e) because the station at Chara is located at a lower elevation than the glaciers (Fig. 1). During the cold season, the 'Siberian High' dominates in the lower troposphere (1.5 to 2 km above the surface), but its influence diminishes with height and, at the elevation of the glaciers (typically > 2 km), this high pressure system is replaced by a trough of low pressure. This decline in atmospheric pressure with elevation over eastern Siberia in the cold season results in significant increases in precipitation with height (Panagiotopoulos *et al*., 2005). As such, precipitation records from Chara may not be entirely representative of the cold season precipitation received by the Kodar glaciers. Correlation between the September-May precipitation record from Chara and data derived from NCEP/NCAR reanalysis (Kalnay *et al*., 1996), which takes terrain elevation into account, is moderate ($r = 0.44$) but statistically significant at the 0.05 level. It is uncertain whether the differences between the two data sets are due to the precipitation gradient or uncertainties in the modelled data. However, neither records exhibit statistically significant trends in September-May precipitation and the accumulation season totals for the periods 1960-1995, 1995-2010 and 1995-2002 are similar.

Shahgedanova *et al.* (2011) reported thinning across the entire surface of the Azarova Glacier (which ranges over ~300 m vertically) and it is likely that the warming-driven thinning observed here has occurred on the other glaciers in the region which span a similar elevation range. Thus, it seems that glaciers in the Kodar Mountains have a higher sensitivity to warming than might be expected from their continental position. Furthermore, glacier thinning is likely to result in englacial debris being exposed at the glacier surface and may also result in additional delivery of supraglacial material through debuttressing of valley sides (cf. Stokes *et al*., 2007), or simply the exposure of greater heights of rockfall-shedding cliff. These processes (thinning/debuttressing leading to an increase in supraglacial debris cover) are consistent with our observations of a reduction in exposed ice. Although we have no measurements of the actual terminus positions of Kodar glaciers (which would be challenging, even in the field), it is likely that terminus retreat will lag the change in exposed ice because thicker debris towards the terminus will insulate buried ice from ablation, compared to exposed ice further up-glacier (cf. Østrem, 1959; Nakawo and Rana, 1999; Popovnin and Rozova, 2002). As the proportion of debris cover increases, therefore, it is likely that it exerts a greater influence on melting rates of adjacent bare ice (see also Demuth *et al*., 2008), setting up a positive feedback that may result in some glaciers becoming entirely debris-covered before they disappear altogether. The steep-sided, sheltered valleys in the Kodar Mountains are conducive to such a process, and our working hypothesis is that some glaciers may evolve into a type of rock glacier, as observed elsewhere (e.g. Johnson, 1980; Ackert, 1998; Monnier, 2007; Ribolini *et al*., 2007; see also discussion in Berthling, 2011). This may have already happened to some glaciers (see discussion of missing glaciers in section 5.1) and, if recent trends continue, a simplistic linear projection of the data in Fig. 11, suggests that this may occur on some glaciers within the next few decades.

Elsewhere in Siberia, Surazakov *et al.* (2007) reported a 7.2% reduction in the surface area of 8 small glaciers in the Aktru River basin of the Russian Altai from 1952 to 2006, with areal loss increasing from 0.9% to 1.6% per decade between 1976 and 2006. A more extensive survey by Shahgedanova *et al*. (2010) found that, in the Altai, glaciers with a similar size to those in the

Kodar (i.e. 0.5 to 1.0 km^2) lost an estimated average of 28% of their area between 1952 and 2004 and their analysis also revealed that shrinkage accelerated after ~1995. In NE Siberia, Ananicheva *et al.* (2005) report post 1950s increases in glacier recession in the Suntar-Khayata Mountains. We suggest that glaciers in Siberia are primarily responding to increased summer temperatures but that those in the Kodar Mountains have shown a relatively recent response (cf. Solomina, 2000). Given that these glaciers are likely to have response times of the order of 10-20 years (cf. Oerlemans *et al*., 1998; De Smedt and Pattyn, 2003), it is likely that the post-1995 reduction in exposed ice observed in this study is a reaction to a warming trend that began in the 1980s, with no compensating increase in accumulation season precipitation.

5.3. Potential topographic controls on glacier recession

Our study reveals no obvious controls on the reduction of exposed ice. Larger and longer glaciers tend to lose more ice in absolute terms, but when areal loss is expressed as a percentage of their original glacier size, smaller and shorter glaciers lose proportionally more ice (cf. Oerlemans *et al*., 1998). Similar results were obtained by Kutuzov and Shahgedanova (2009), who found that glaciers <1 km^2 in the Terskey-Alatoo (inner Tien Shan) lost an average of 34% between the mid-19th century and 2003, whereas those >10 km^2 lost only 10% of their area. Likewise, Shahgedanova *et al*. (2010) found that glaciers <1 km^2 in the Altai lost 28% but those >5 km^2 lost only 17% between 1952 and 2004 (see also; Ramírez *et al*., 2001; Granshaw and Fountain, 2006; Paul and Haeberli, 2008; Tennant *et al*., 2012). As noted by Tennant *et al*. (2012), these observations may generally be explained by the fact that smaller glaciers have higher volume-to-area and perimeter-to-area ratios, making them shrink faster than larger glaciers for any given ablation rate (Granshaw and Fountain, 2006), and become more susceptible to radiation from surrounding terrain (Demuth *et al.,* 2008).

No obvious control on the shrinkage of exposed ice is exerted by aspect (Fig. 9), despite the fact that it is an important (and statistically significant) control on glacier location. Indeed, whilst glaciers which face SE ($n = 2$) show the highest recession rates (also detected by Kutuzov and Shahgedanova, 2009), glaciers facing N, NW and NE show rates of recession that are only marginally lower (Fig. 9). This is somewhat unexpected, and emphasises that a number of additional factors may be important in modulating recession (e.g. supraglacial debris cover, altitude, etc.). Similar conclusions were reached by DeBeer and Sharp (2009) and Tennant *et al*. (2012), who noted the lack of a favoured aspect for glaciers that had shrunk in the Monashee Mountains, British Columbia, and the Canadian Rocky Mountains, respectively.

We find no significant relationship between glacier shrinkage and elevation characteristics (minimum, maximum), or gradient. This is probably related to the small sample size and the relatively narrow range of elevations of Kodar glaciers (minimum elevation only varies by ~500 m, from 1910 to 2443 m; maximum elevations range from 2193 to 2798 m). It is also likely that when glaciers recede into deep valleys, any further wastage is increasingly influenced by their topographic setting (which may also influence delivery of supraglacial-debris cover). Indeed, a potentially important control is that of topographic shading, which is likely to 'protect' glaciers from recession compared to those that are more exposed (e.g. Paul and Haeberli, 2008; Evans, 2009). DeBeer and Sharp (2009), for example, showed that some very small glaciers (<0.4 km^2) in the Monashee Mountains in British Columbia had not changed appreciably between 1951 and 2004 and they attributed this to favourable topographic settings that are sheltered from direct solar radiation and typically reside in sites that receive additional mass input from avalanching or wind drift onto leeward slopes. Although wind speeds are unlikely to be high in eastern Siberia in winter, even at high elevations, some deep valleys in the Kodar Mountains are conducive for the deposition of wind-blown snow drifts. Those glaciers nourished by this process and which receive more shading are likely to undergo slower rates of recession than those that are more exposed. However, our analysis of potential clear sky radiation revealed that there was no correlation to the shrinkage of debris-free ice. In this respect, DeBeer and Sharp (2009) pointed out that whilst glaciers located at relatively lower elevations are more sheltered and generally receive less clear-sky solar radiation than those at higher elevations (i.e. helping to preserve them), glaciers in more exposed sites are generally at higher elevations and are therefore subjected to lower temperatures and are more likely to retain snow cover which reduces ablation (i.e. also helping to preserve them). Clearly, it is difficult to predict the response of small glaciers to a given change in climate because of the multitude of inter-related factors that modulate their response. A similar conclusion was reached by Granshaw and Fountain (2006) who found no significant relationships between glacier recession and aspect, slope or elevation, in the North Cascades National Park, Washington, USA.

6. Conclusions

Mountain glaciers are sensitive indicators of climate change, and numerous studies report their decline from around the world as a result of recent climatic warming (Dyurgerov and Meier, 2000; Kaser *et al*., 2006). Generally, smaller glaciers (e.g. <2 km^2) are thought to respond most rapidly to a given change in climate (Oerlemans *et al*., 1998) and there are reports of disappearances in a number of regions (e.g. Granshaw and Fountain, 2006; De Beer and Sharp, 2009; Federici and Pappalardo, 2010; Tennant *et al*., 2012), necessitating continued monitoring and further investigation of the factors that influence glacier shrinkage and their ultimate demise. This paper reports the first comprehensive multi-year remote sensing survey of glaciers in the Kodar Mountains, SE Siberia, and compares data on the extent of exposed ice in 1995, 2001 and 2010 with those compiled from the first assessment in the late 1950s (Preobrazhenskiy, 1960) and other previous inventories.

We report 34 glaciers, including four glaciers not included in the original inventories (Preobrazhenskiy, 1960; KL: Novikova and Grinberg, 1972) and the WGI. Comparison to glacier inventory data from the 1960s and 70s (and inspection of declassified imagery from 1964), indicates that the total area of exposed ice remained relatively stable from the 1960s to 1995 (between 11 and 13 km^2) but then dramatically reduced to 9.53 (±0.29) km^2 in 2001 and to 7.01 (±0.23) km^2 in 2010. This indicates a ~40% reduction in a 15 year period, which coincides with a strong warming trend in June-July-August temperatures initiated in the 1980s (cf. Shahgedanova *et al*., 2011). Thus, although these cold, continental glaciers are thought to be less 'sensitive' compared to their more maritime counterparts (cf. Oerlemans and Fortuin, 1992, Solomina, 2000), it appears that in recent decades they have responded quite rapidly to a warming trend in this region. Furthermore, it is likely that buried ice on the debris-covered tongues of these glaciers will be protected, such that the overall glacier recession will lag the recession of exposed ice and may eventually result in entirely debris-covered glaciers, possibly within the next few decades, based on a simple linear extrapolation of their recent decline (Fig. 11). Finally, although smaller and shorter glaciers have tended to lose a greater proportion of their area than those that are larger and longer, we find no significant relationships between glacier shrinkage and aspect, radiation or elevation characteristics. This is probably because glaciers in the Kodar Mountains occupy a relatively narrow elevation range and because the specific response (and potential disappearance) of small (<2 km^2) glaciers becomes increasingly modulated by local topographic setting and debris cover characteristics (cf. De Beer and Sharp, 2009; Anderson and Mackintosh, 2012; Tennant *et al*., 2012).

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Tables:

Table 1: Total number and area of exposed ice for glaciers in the Kodar Mountains, see Fig. 3 for corresponding map with Katalog Kednikov (KL) numbers

Glacier ID from Preobraz -henskiy (1960), see Fig. 1.	Glacier ID from WGI (last two digits refer to number in KL (Novikova and Grinberg, 1972)	Glacier name or number (last two digits from WGI ID), see Fig. 3	Area of exposed ice ca. 1963 from the KL (km^2)	Area of exposed ice in 1995 (km^2)	Area of exposed ice in 2001 (km^2)	Area of exposed ice in 2010 (km^2)
20	SU5D17201001	01	0.2	0.14 (±0.04)	0.05 (±0.01)	0.03 (±0.01)
28	SU5D17201002	02	0.3	0.23 (±0.07)	0.08 (±0.02)	0.06 (±0.02)
11	SU5D17201003	03	0.6	0.40 (±0.08)	0.41 (±0.07)	0.27 (±0.04)
29	SU5D17201004	ZABAIKALIETZ	0.1	0.24 (±0.07)	0.19 (±0.03)	0.13 (±0.03)
10*	SU5D17201005	SYGYKTINSKIY	0.6	0.56 (±0.11)	0.47 (±0.05)	0.33 (±0.04)
9	SU5D17201006	KOLOSOV	0.6	0.51 (±0.09)	0.44 (±0.05)	0.38 (±0.04)
5	SU5D17201007	07	0.3	0.30 (±0.12)	0.22 (±0.06)	0.06 (±0.02)
19	SU5D17201008	08	0.3	0.30 (±0.15)	0.18 (±0.05)	0.11 (±0.03)
18	SU5D17201009	09	0.5	0.44 (±0.11)	0.35 (±0.04)	0.29 (±0.04)
17	SU5D17201010	10	0.5	0.56 (±0.10)	0.30 (±0.05)	0.22 (±.0.05)
16	SU5D17201011	TIMASHEV	0.5	0.44 (±0.10)	0.33 (±0.05)	0.30 (±0.04)
15	SU5D17201012	SOVIET GEOGRAPHERS	0.8	1.44 (±0.28)	1.20 (±0.15)	1.00 (±0.12)
22	SU5D17201013	13	0.7	0.22 (±0.07)	0.17 (±0.03)	0.16 (±0.03)
25	SU5D17201014	14	0.4	0.36 (±0.08)	0.32 (±0.04)	0.21 (±0.03)
27	SU5D17201015	15	0.4	0.23 (±0.06)	0.29 (±0.03)	0.19 (±0.03)
26	SU5D17201016	16	0.1	0.17 (±0.09)	0.15 (±0.05)	0.07 (±0.02)
23	SU5D17201017	17	0.1	0.19 (±0.11)	0.16 (±0.03)	0.13 (±0.02)
24	SU5D17201018	18	0.2	0.21 (±0.06)	0.09 (±0.02)	0.03 (±0.01)
21	SU5D17201019	19	0.7	0.18 (±0.05)	0.12 (±0.03)	0.09 (±0.03)
14	SU5D17201020	AZAROVA	1	0.63 (±0.16)	0.56 (±0.07)	0.53 (±0.07)
1	SU5D17201021	YABLONSIY	0.5	0.34 (±0.14)	0.34 (±0.05)	0.28 (±0.04)
2	SU5D17201022	KAUFMAN	0.4	0.32 (±0.10)	0.31 (±0.05)	0.22 (±0.03)
4	SU5D17201023	23	0.2	0.20 (±0.15)	0.18 (±0.03)	0.12 (±0.02)
3	SU5D17201024	BOBIN	0.6	0.86 (±0.24)	0.75 (±0.07)	0.59 (±0.06)
8	SU5D17201025	NIKITIN	0.3	0.16 (±0.09)	0.12 (±0.02)	0.07 (±0.02)
10*	SU5D17201026	SYGYKTINSKIY	0.6	0.44 (±0.12)	0.51 (±0.07)	0.38 (±0.06)
13	SU5D17201027	27	0.5	0.29 (±0.13)	0.26 (±0.04)	0.15 (±0.03)
12	SU5D17201028	28	0.6	0.05 (±0.03)	0.04 (±0.02)	0.03 (±0.01)
6	SU5D17201029	29	*No data*	0.13 (±0.05)	0.08 (±0.02)	0.07 (±0.02)
30	SU5D17201030	30	*No data*	0.22 (±0.09)	0.15 (±0.03)	0.12 (±0.03)
		Total	**12.60**	**10.76 (±0.70)**	**8.82 (±0.28)**	**6.62 (±0.22)**

			(n = 28)	*(n = 30)*	*(n = 30)*	*(n =30)*
Not identified	*Not identified*	33	*Not identified*	0.30 (±0.08)	0.21 (±0.04)	0.02 (±0.01)
Not identified	*Not identified*	34	*Not identified*	0.40 (±0.12)	0.32 (±0.05)	0.26 (±0.05)
Not identified	*Not identified*	35	*Not identified*	0.11 (±0.04)	0.09 (±0.03)	0.06 (±0.01)
Not identified	*Not identified*	36	*Not identified*	0.15 (±0.07)	0.08 (±0.02)	0.05 (±0.01)
		Total	**12.60** *(n = 28)*	**11.72 (±0.72)** *(n = 34)*	**9.53 (±0.29)** *(n = 34)*	**7.01 (±0.23)** *(n = 34)*

¶ Note: following convention, errors of totals are calculated by the Pythagorean root-sum-squares rule, which assumes that individual errors are independent of each other.

*Preobrazhenskiy (1960) depicts this glacier as a contiguous ice mass whereas the Katalog Lednikov (KL, 1972) and WGI split it into two connected glaciers.

Table 2: Changes in debris-free glacier area in the Kodar Mountains

Date of inventory (if known) and number of glaciers (n)	Ref.	Area of debris-free glacier ice (km^2)			Change since previous time step (km^2)			Change since previous time step (%)			Rate of change since previous time-step ($km^2\ a^{-1}$)			Rate of change since previous time-step ($\%\ a^{-1}$)		
		Meas.	*Min.*	*Max.*	**Meas.**	*Min.*	*Max.*	**Meas.**	*Min.*	*Max.*	**Meas.**	*Min.*	*Max.*	**Meas.**	*Min.*	*Max.*
1963* **(n = 28)**	Katalog Lednikov (Novikova and Grinberg, 1972)	**12.6**	*n/a*	*n/a*	**n/a**	*n/a*	*n/a*	**n/a**	*n/a*	*n/a*	**n/a**	*n/a*	*n/a*	**n/a**	*n/a*	*n/a*
1974 **(n= 39)**	Plastinin and Plyushin (1979); Plastinin (1998)	**12**	*n/a*	*n/a*	**-0.06**	*n/a*	*n/a*	**4.8%**	*n/a*	*n/a*	**0.05**	*n/a*	*n/a*	**0.43**	*n/a*	*n/a*
17 Jul 1995 **(n = 34)**	This study	**11.72 (±0.72)**	*11*	*12.44*	**-0.28**	*0.44*	*-1*	**-2.33**	*3.67*	*-8.33*	**-0.01**	*0.02*	*-0.05*	**-0.11**	*0.17*	*-0.40*
11 Jul 2001 **(n = 34)**	This study	**9.53 (±0.29)**	*9.24*	*9.82*	**-2.19**	*-1.9*	*-2.48*	**-18.69**	*-15.83*	*-21.16*	**-0.37**	*-0.32*	*-0.41*	**-3.11**	*-2.64*	*-3.53*
2001 **(n = 41)**	Osipov (2010)	**7.10**														
27 Jul 2010 **(n = 34)**	This study	**7.01 (±0.23)**	*6.78*	*7.24*	**-2.52**	*-2.29*	*-2.75*	**-26.44**	*-19.08*	*-28.86*	**-0.28**	*-0.25*	*-0.31*	**-2.94**	*-2.12*	*-3.21*

Figure Captions:

Fig. 1: Location map of the Kodar Mountains in Transbaikalia (A). Glaciers are restricted to the area within the black box on (B), see Figs. 2 and 5. The highest peak (Baikal Amur Magistral, 'Pik BAM') is located with a yellow dot.

Fig. 2: The first map of glaciers in the Kodar Mountains, redrawn from Preobrazhenskiy (1960). The location of 31 glaciers is marked (grey shading, numbered), with one denoted with a '?' in the far south-west of the study area. Numbers are from Preobrazhenskiy (1960) but corresponding numbers from the Russian Catalogue of Glaciers (Kalatolog Lednikov (KL): Novikova and Grinberg, 1972) are shown in Table 1, which are used throughout the manuscript. Thus, glaciers shown in Fig. 3 are labelled here as 14 (20 on Fig. 3), 15 (12) and 16 (11).

Fig. 3: Photo-mosaic illustrating the typical topographic setting of glaciers in the Kodar Mountains. Looking due south, the numbers refer to glacier IDs in the Katalog Lednikov (KL: Novikova and Grinberg, 1972) and World Glacier Inventory: 20 = Azarova Glacier; 12 = Soviet Geographers Glacier, which is the largest in the region (partly hidden); and 11 = Timashev. The highest peak (Baikal Amur Magistral: 3,072 m) is also shown (photo-mosaic courtesy of Vladimir Sheinkman).

Fig. 4: Results from testing of three main mapping methods for glacier delineation (cf. Paul, 2000; Pellika and Rees, 2010) on a Landsat ETM+ image from 27 July 2010: (A) yellow

outline shows the result of manual digitising on a false colour composite (5, 4, 3) of the Azarova Glacier (number 20: see photograph in Fig. 1), giving an area of 0.528 km^2 (this outline shown on all panels for comparison); (B) shows the results of a supervised classification of the entire scene using six bands (bands 1-5 and 7) and 7 classes (glacier ice, debris-covered ice, debris cover, exposed bedrock, cloud, water, vegetation) and gives the glacier area as 0.448 km^2 (not including scan line errors contiguous with the main glacier); (C) is an unsupervised classification and gives an area of 0.368 km^2 (blue area, including area lost to scan line error within the main glacier); (D) shows a ratio image of ETM+ band 4/band 5 after applying a threshold value of 1.8 and a median filter (3 x 3), following GLIMS (Global Land Ice Measurements from Space) guidelines (Rau *et al*., 2004) and gives an area of 0.390 km^2; (E) as in (D) but with a threshold value of 2 (cf. Paul *et al*., 2007; Gjermundsen *et al*., 2011) and gives an area of 0.379 km^2; (F) as in (E) but using ETM+ band3/band5 and gives an area of 0.536 km^2.

Fig. 5: (A) Landsat ETM+ pan-sharpened satellite image (5, 4, 3) from 27th July 2010 showing location of 34 glaciers mapped in the Kodar Mountains (yellow outlines). Numbers correspond to those in the KL/WGI, see Table 1. Compare to Fig. 2 and note the location of four glaciers (black rectangle shown in (B)) that were not included in the original glacier inventories (e.g. Preobrazhenskiy, 1960; KL/WGI) but which do appear in Plastinin and Plyusnin (1979) and Oispov (2010). Following Plastinin and Plyusnin (1979), we refer to them as numbers 33-36, from west to east.

Fig. 6: Landsat ETM+ pan-sharpened satellite image (5, 4, 3) from 27th July 2010 showing the shrinkage of exposed ice on 11 glaciers around Pik BAM from 1995 (red), to 2001 (green) and 2010 (yellow).

Fig. 7: Frequency distribution of glacier sizes (exposed ice only) in 1995, 2001 and 2010.

Fig. 8: Bar chart of the percentage reduction of exposed ice between 1995 and 2010 ($n = 34$; glacier numbers refer to those in Fig. 4). Mean glacier shrinkage 45% (denoted by dotted line).

Fig. 9: Area of exposed glacier ice in 1995 plotted against both the total area loss in km^2 (A) and the percentage area loss (B) from 1995 to 2010. The relationship between glacier size and area loss is statistically significant ($r^2 = 0.56$; $p < 0.0001$) but this relationship is reversed and not quite significant when expressed as a percentage loss ($r^2 = 0.11$; $p <0.053$). Similar relationships for glacier length are shown in (C) and (D) where both are significant ($r^2 = 0.31$; $p <0.0006$; $r^2 = 0.16$; $p <0.02$).

Fig. 10: Mean percentage exposed glacier ice area loss from 1995 to 2010 according to glacier aspect.

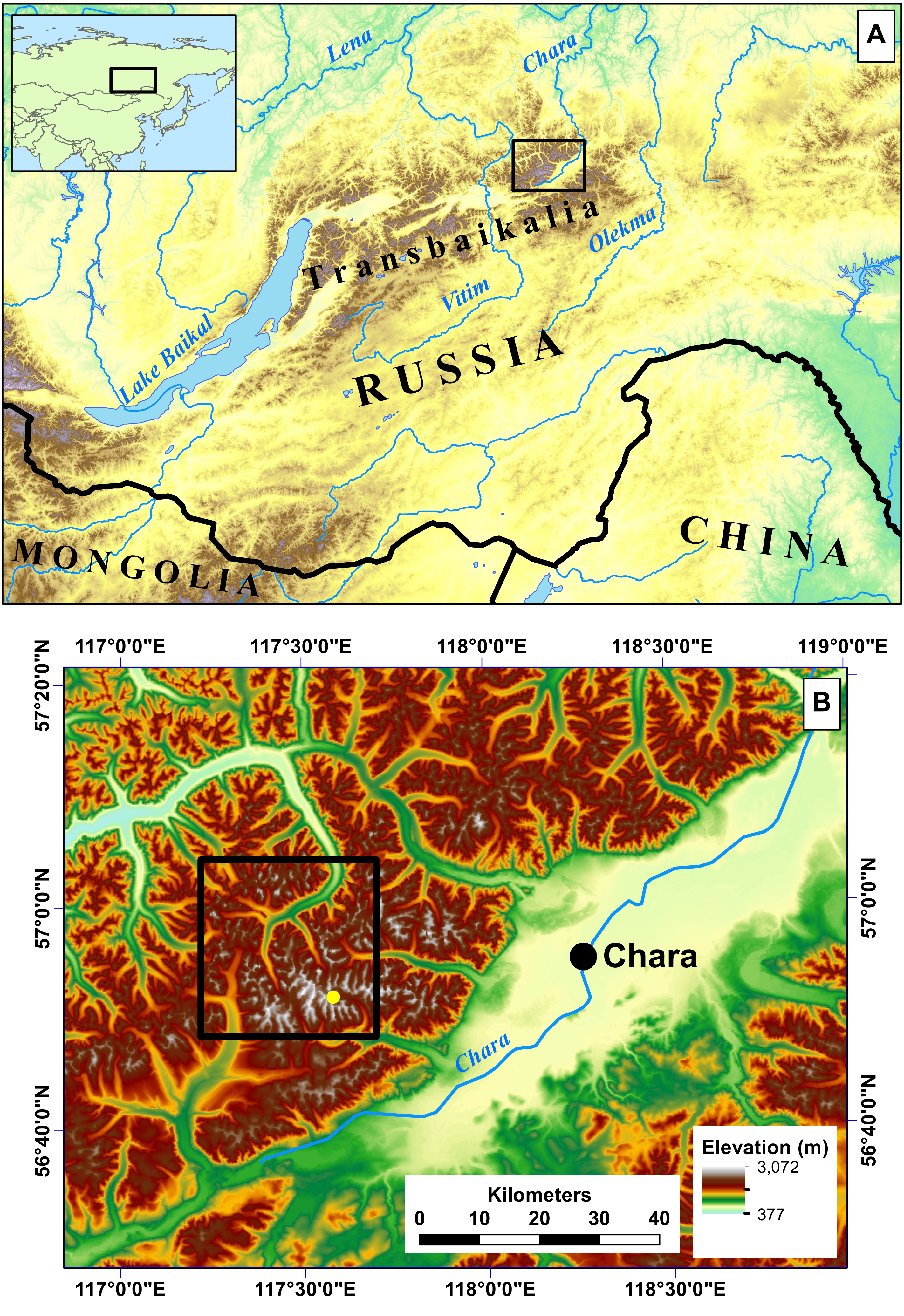
Fig. 11: Total area of exposed ice through time in the Kodar Mountains. Data from 1963 refer to those in the Katalog Lednikov (Novikova and Grinberg, 1972; which omits glaciers 33-36) and those from 1974 are taken from Plastinin and Plyushin (1979), see Table 2.

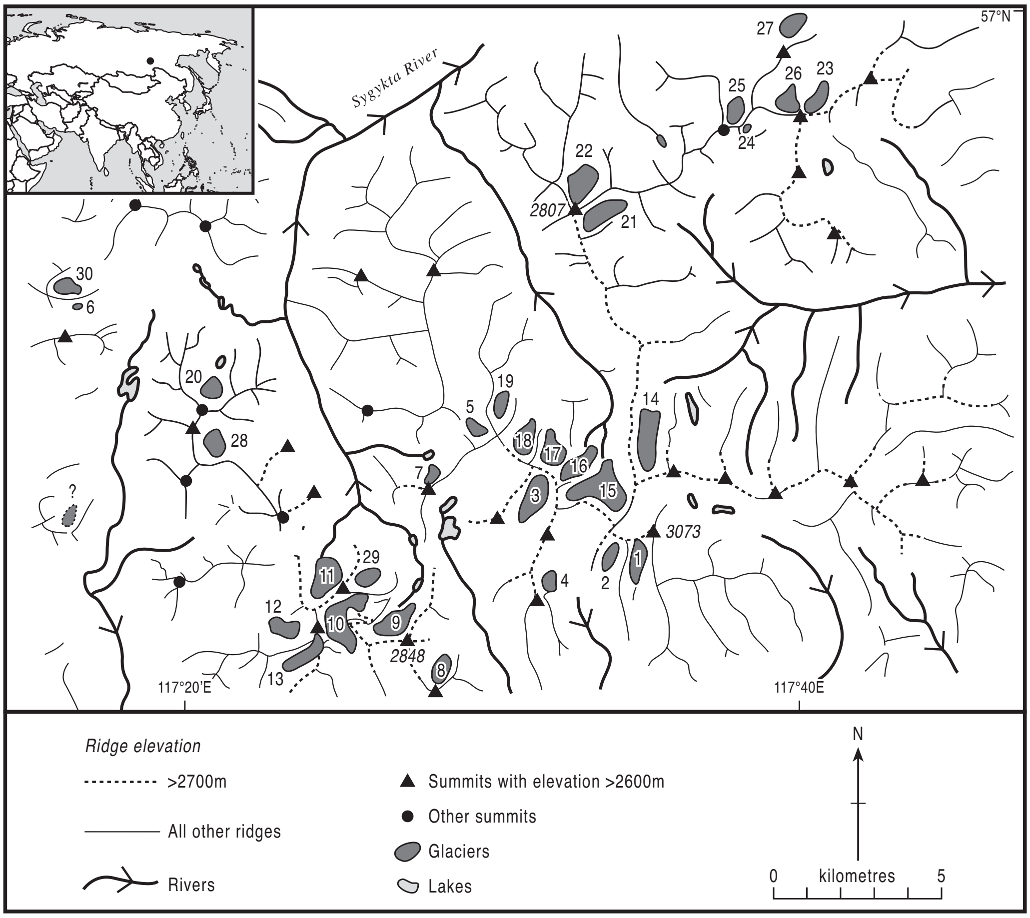
Osipov's (2010) anomalously low value for 2001 is also shown (open circle). Errors bars for our data in 1995, 2001 and 2010 (see also Table 1) are calculated by the conventional Pythagorean root-sum-squares rule, which assumes that errors for individual glaciers are independent of each other.

Fig. 12: Comparison of 8 glaciers on a pan-sharpened ETM+ image from July 2010 (5, 4, 3) and panchromatic CORONA images from July 1964.

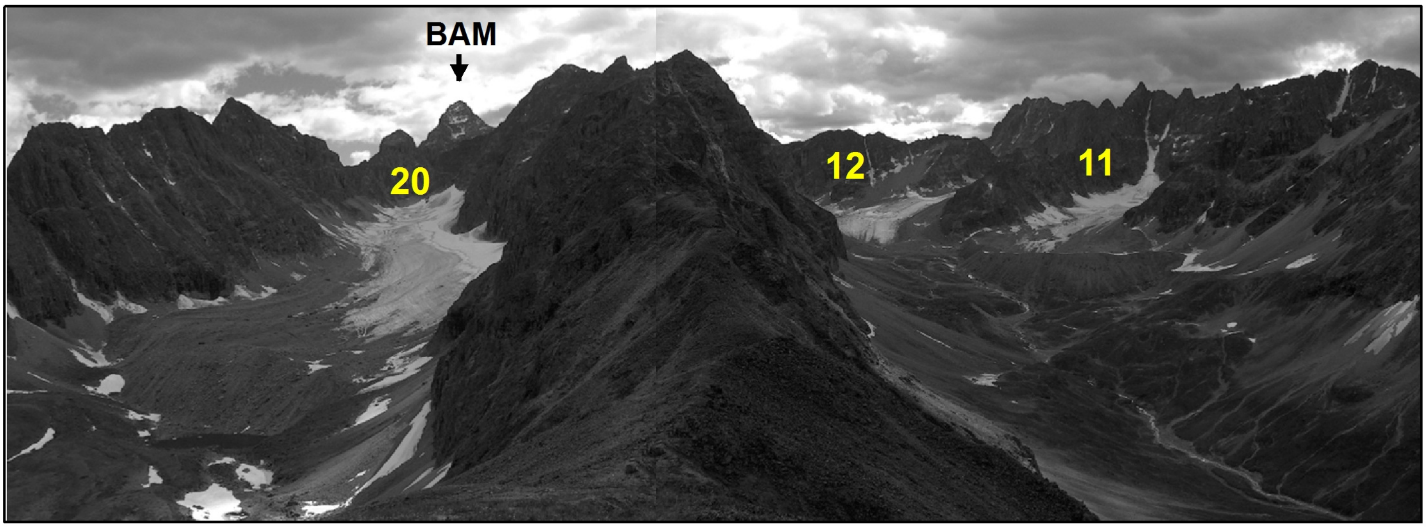
Fig. 13: Time series of seasonal temperatures at the Chara meteorological station (a-d) and accumulation and ablation season precipitation from Chara and NCEP/NCAR reanalysis averaged over the region 56.5 to 57.5 ° N and 117-118 ° E (e-f). Thin solid line in (a-d) shows time-series average and ± two standard deviations are shown as dashed lines.

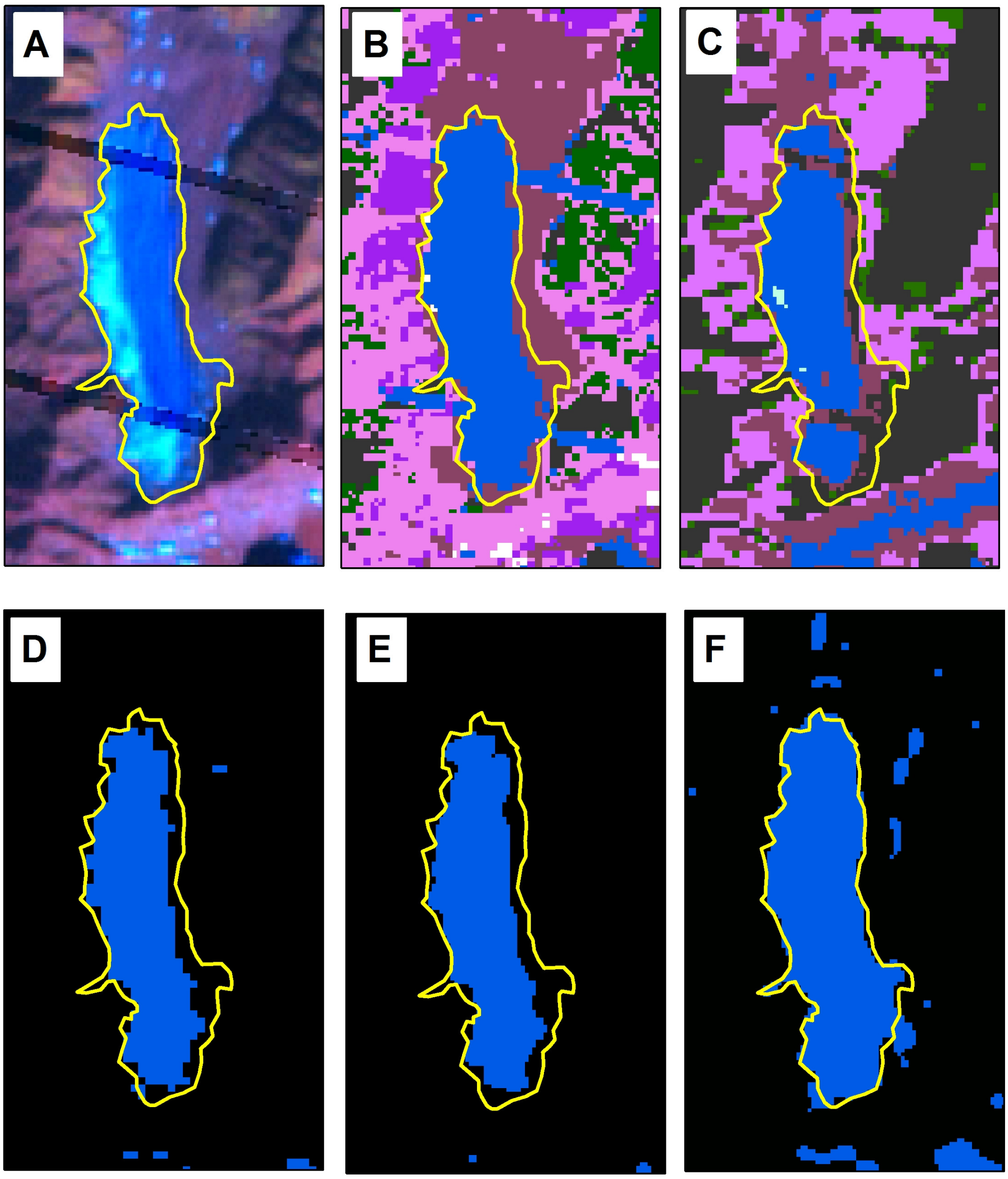
Fig. 14: Decadal mean June-July-August temperature records at Chara.

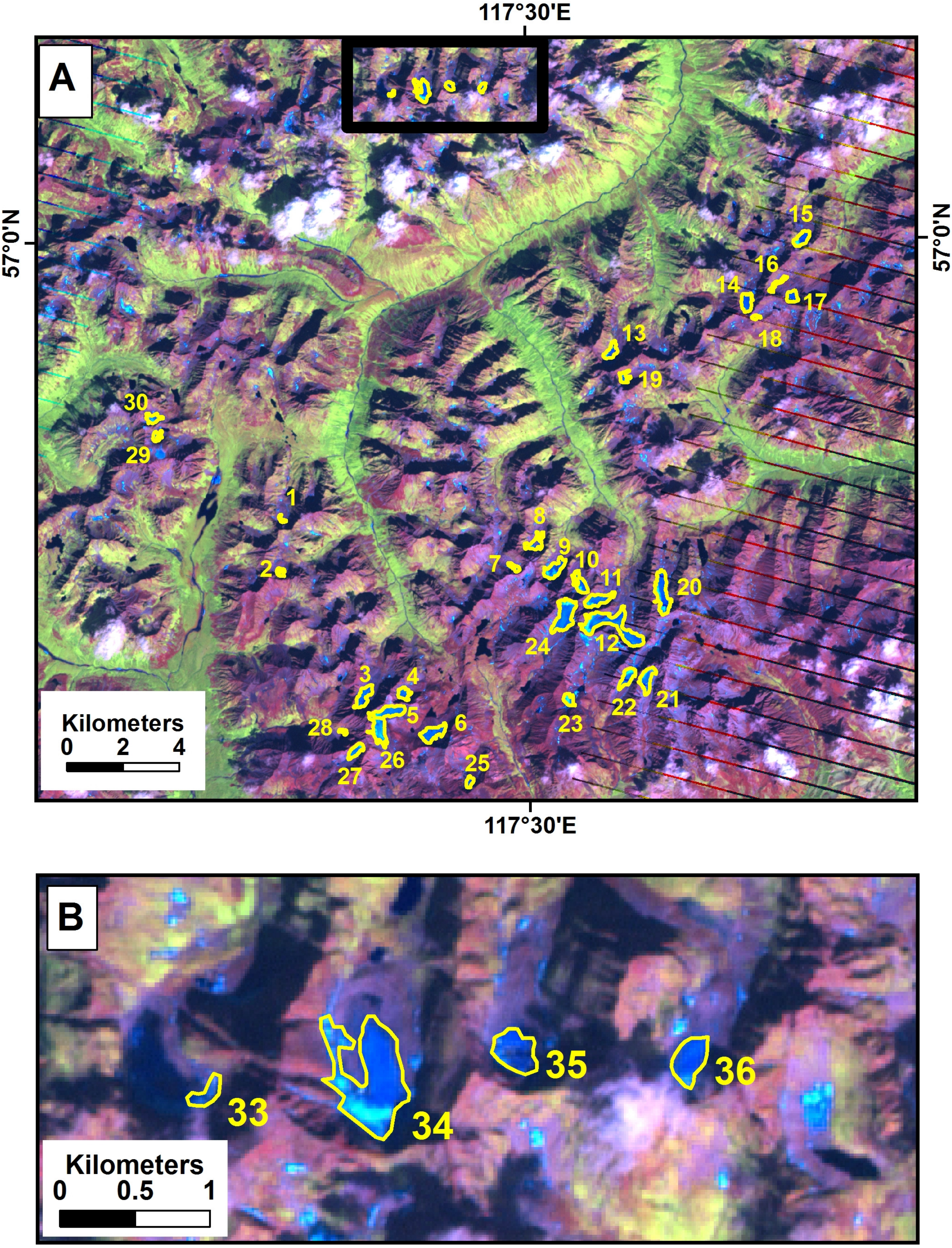

A
Lena
Chara
Transbaikalia
Olekma
Vitim
Lake Baikal
RUSSIA
MONGOLIA
CHINA
B
117°0'0"E
117°30'0"E
118°0'0"E
118°30'0"E
119°0'0"E
57°20'0"N
57°0'0"N
56°40'0"N
Chara
Chara
Kilometers
0 10 20 30 40
Elevation (m)
3,072
377



Sygykta River
57°N
117°20'E
117°40'E
2807
3073
2848
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
?
Ridge elevation
>2700m
All other ridges
Rivers
Summits with elevation >2600m
Other summits
Glaciers
Lakes
N
0
kilometres
5


BAM
20
12
11


A
B
C
D
E
F


A
117°30'E
57°0'N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
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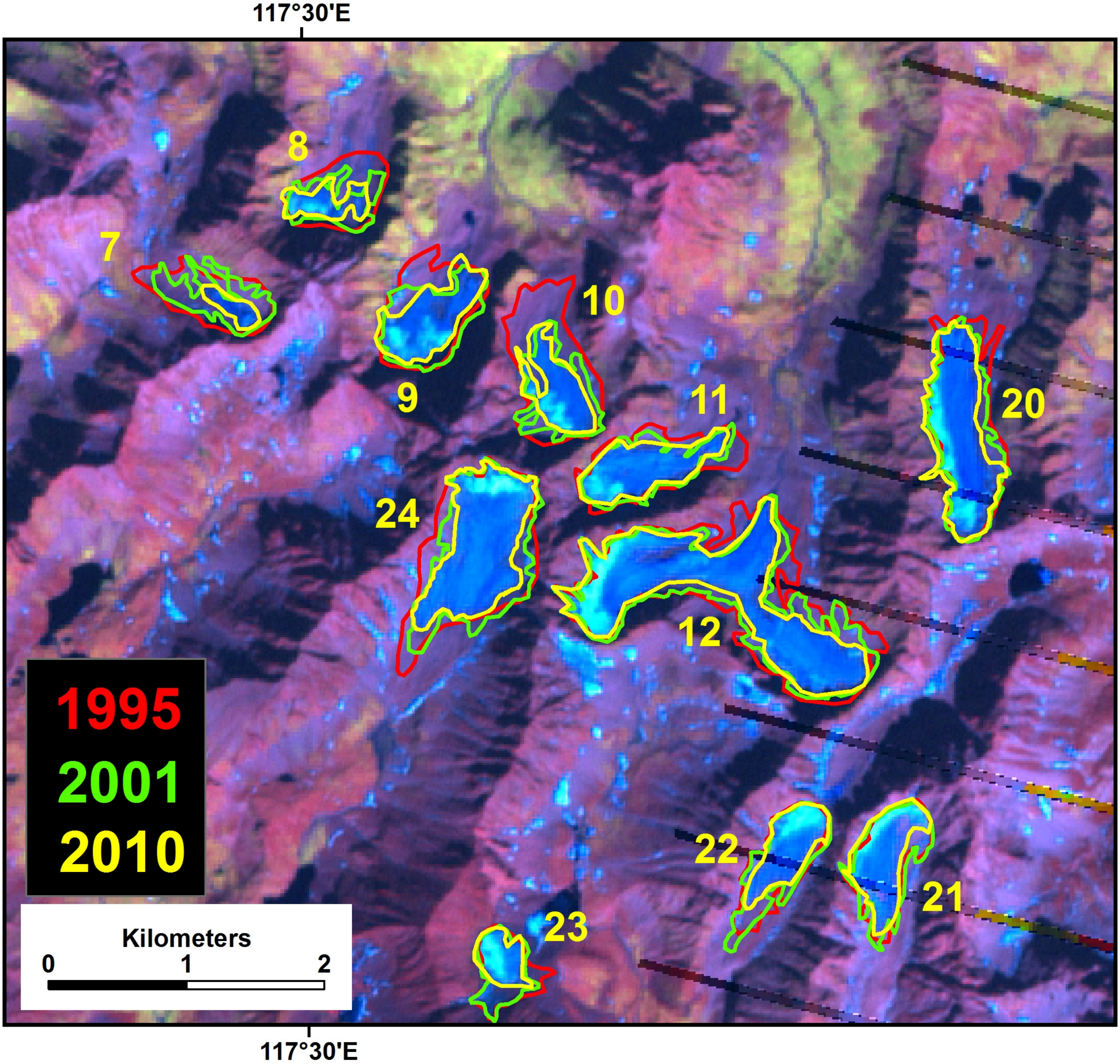
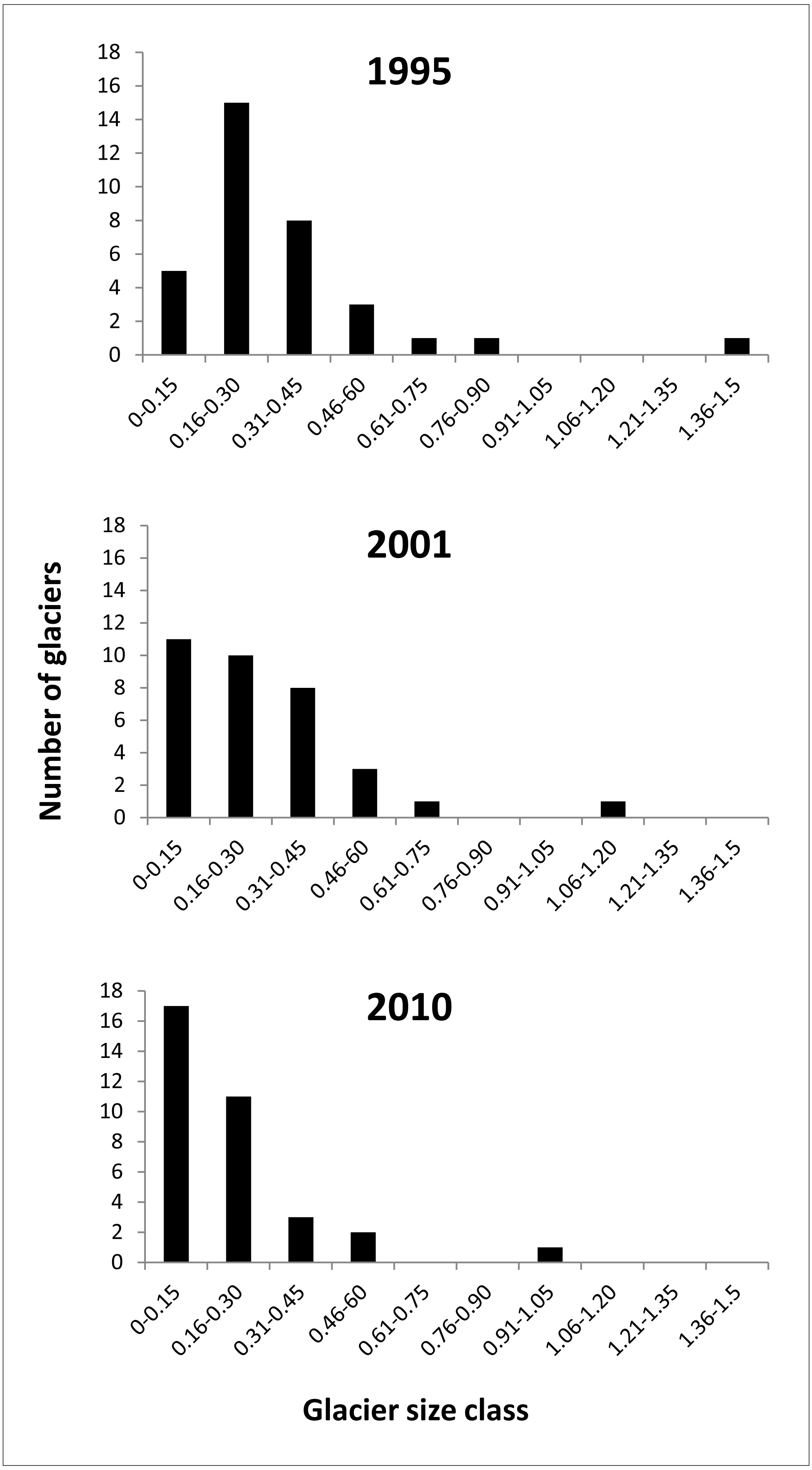
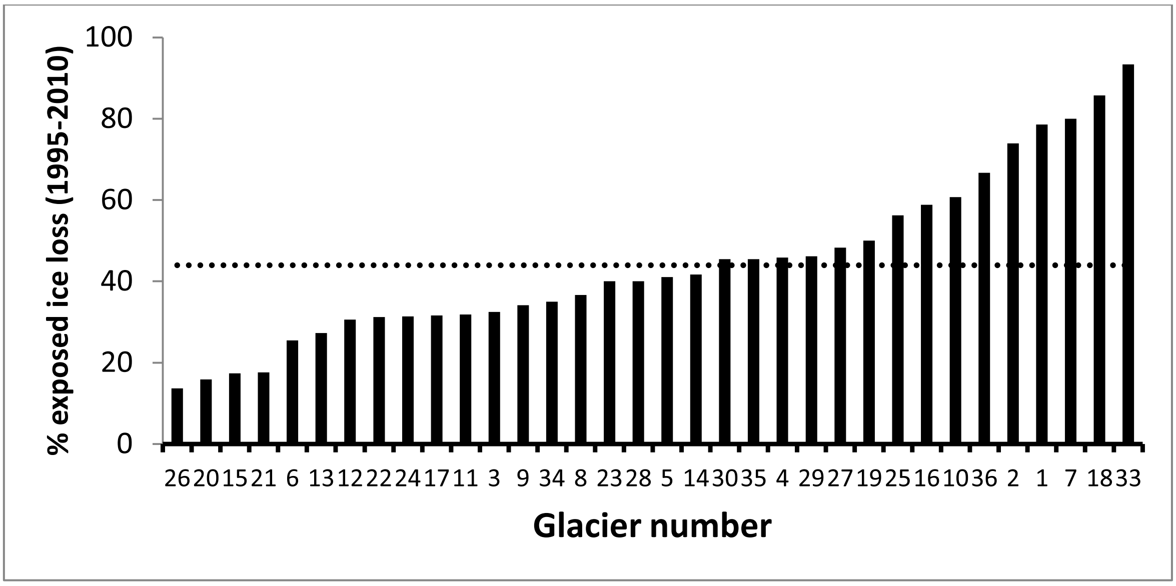
28
29
30
Kilometers
0 2 4
B
33
34
35
36
Kilometers
0 0.5 1

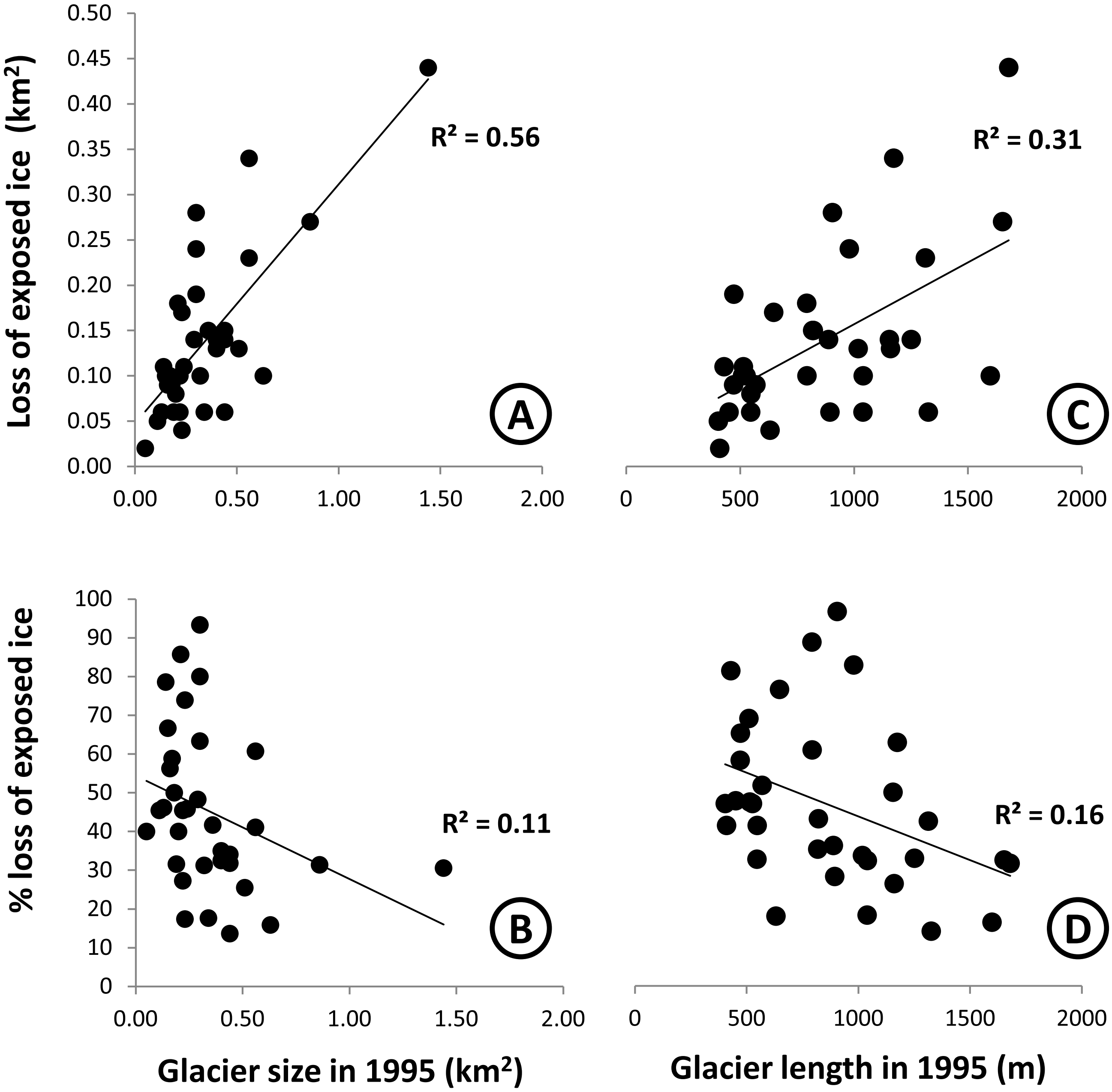

117°30'E
8
7
9
10
11
20
24
12
1995
2001
2010
22
21
23
Kilometers
0
1
2
117°30'E

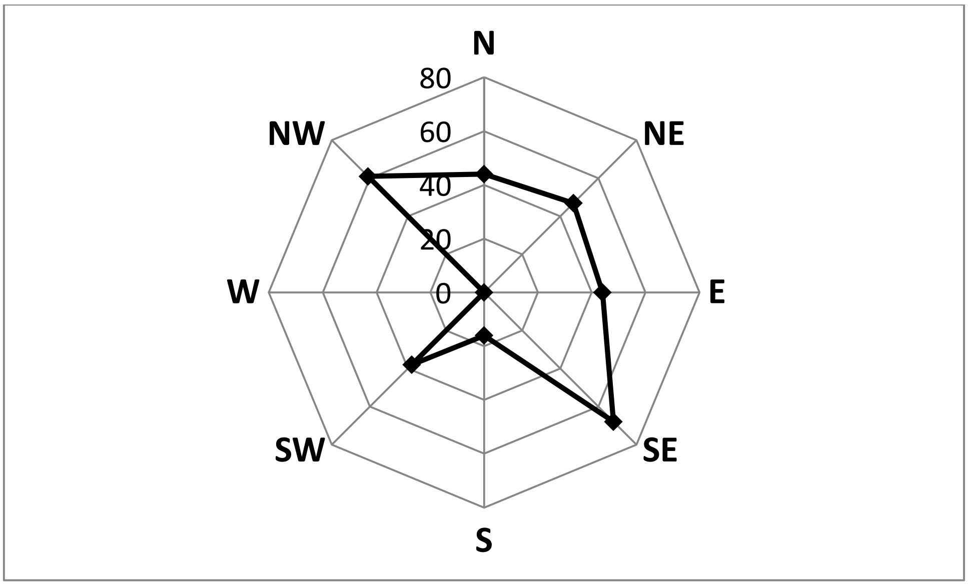


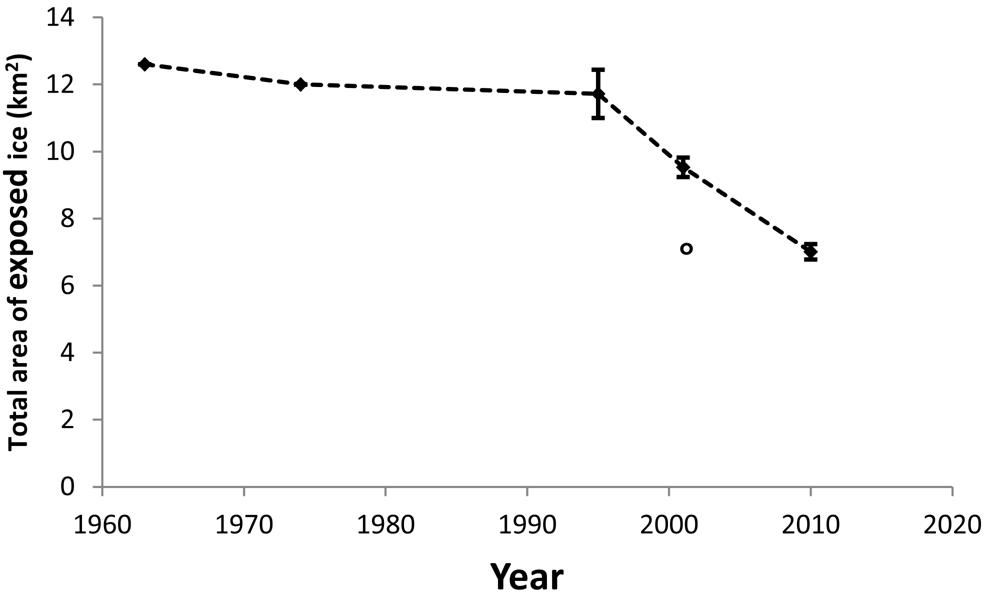
1995
2001
2010
Number of glaciers
Glacier size class
0-0.15
0.16-0.30
0.31-0.45
0.46-60
0.61-0.75
0.76-0.90
0.91-1.05
1.06-1.20
1.21-1.35
1.36-1.5



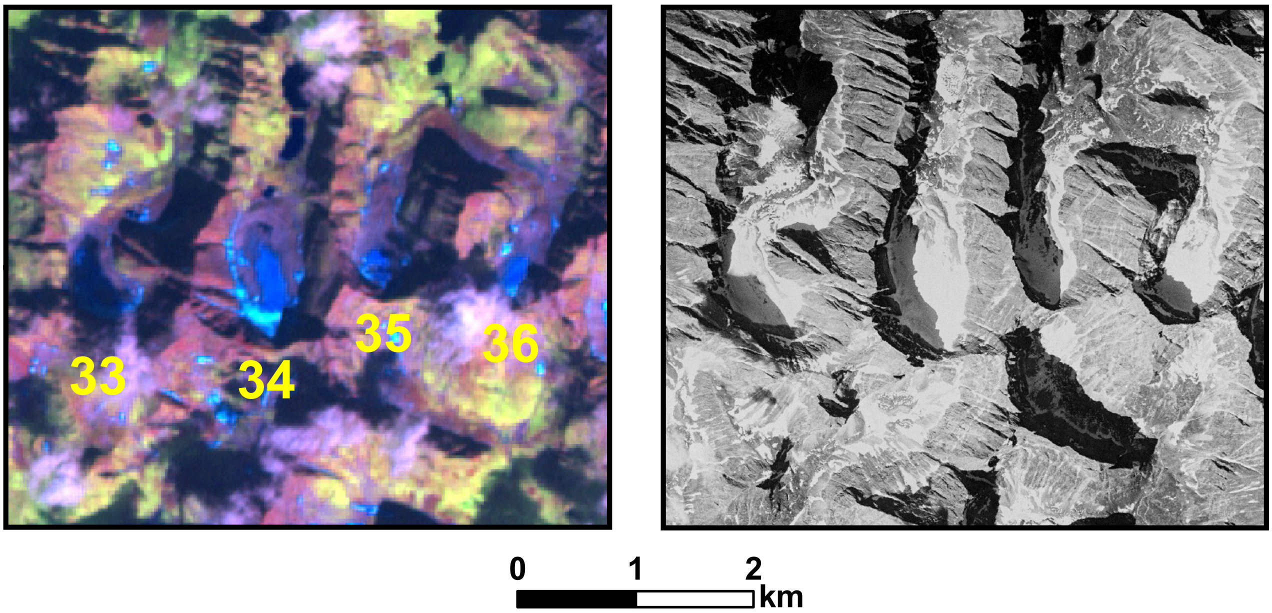
100
80
60
40
20
0
% exposed ice loss (1995-2010)
26 20 15 21 6 13 12 22 24 17 11 3 9 34 8 23 28 5 14 30 35 4 29 27 19 25 16 10 36 2 1 7 18 33
Glacier number

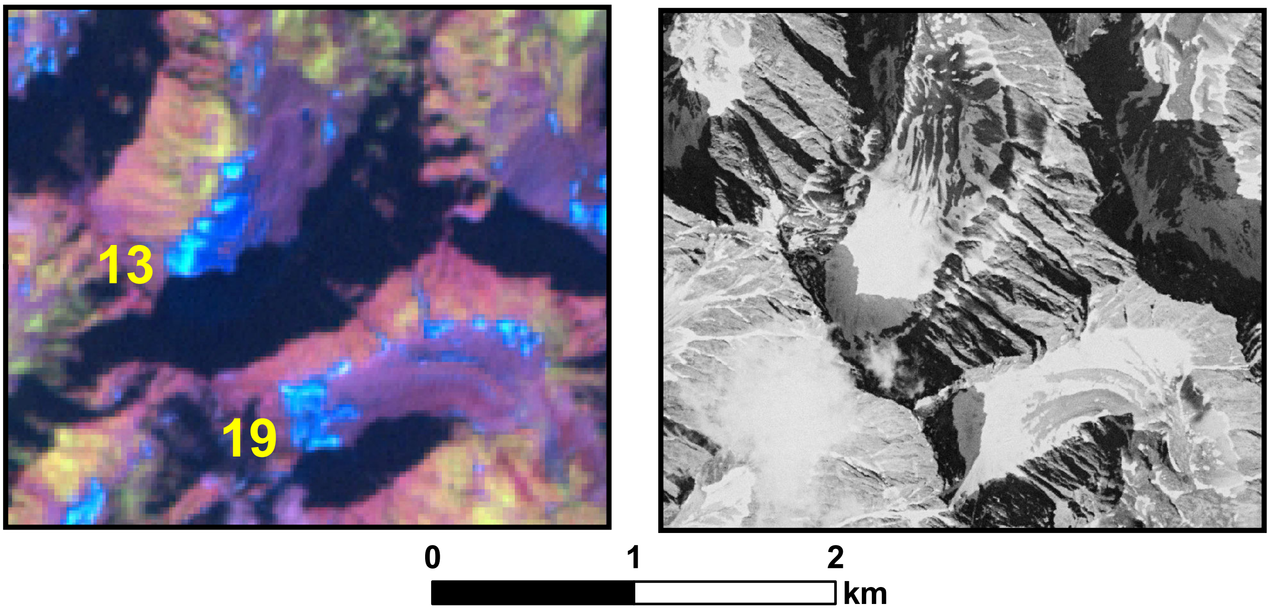

Loss of exposed ice (km²)
R² = 0.56
A
R² = 0.31
C
% loss of exposed ice
R² = 0.11
B
R² = 0.16
D
Glacier size in 1995 (km²)
Glacier length in 1995 (m)

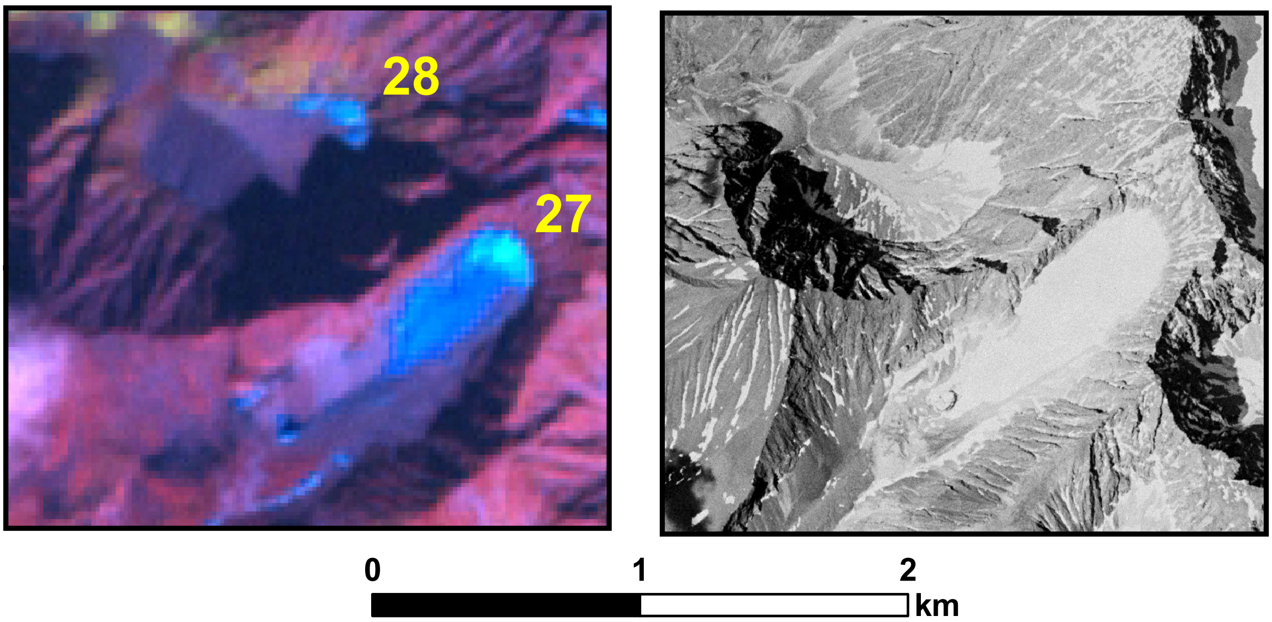

N
NE
E
SE
S
SW
W
NW
80
60
40
20
0

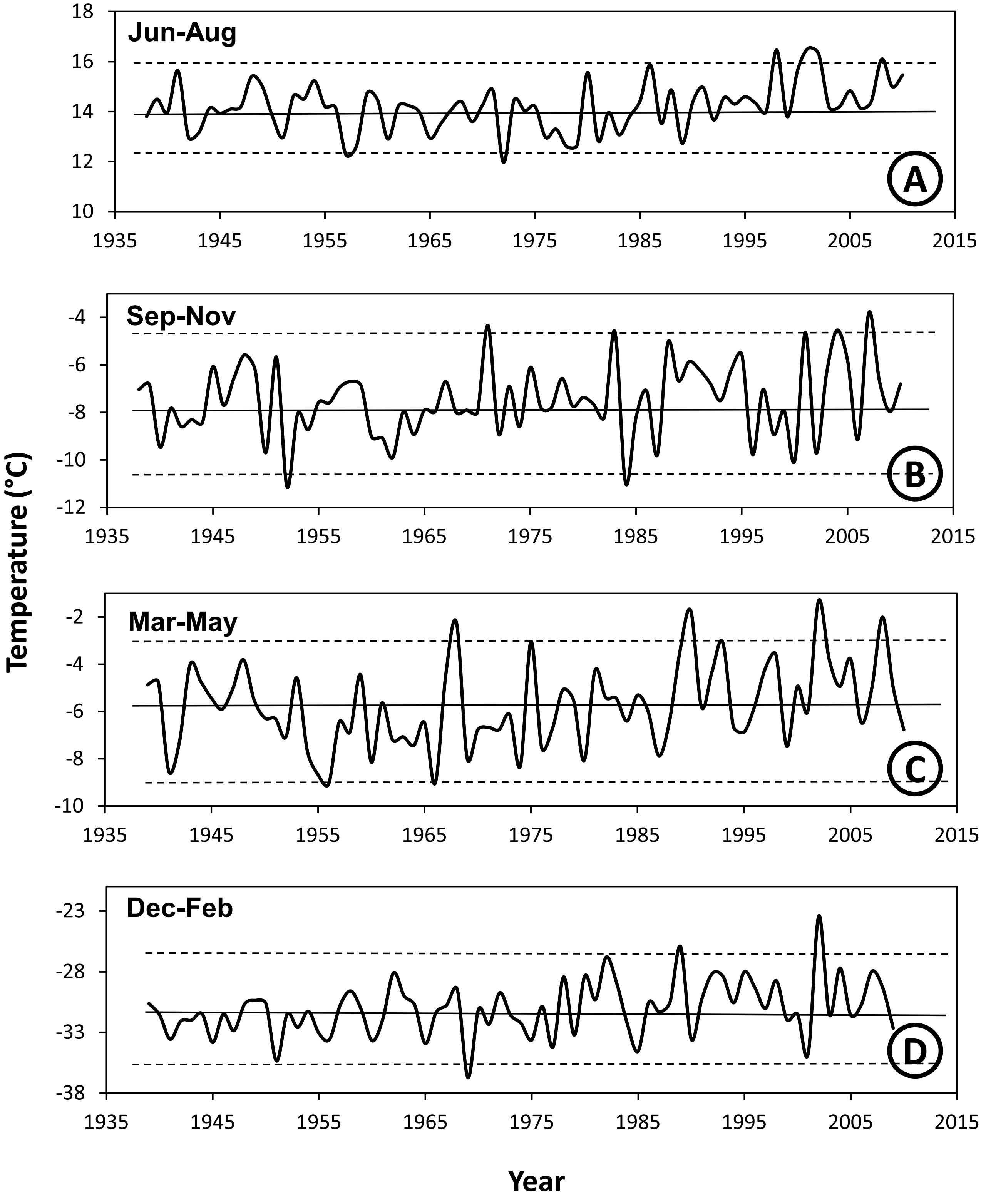


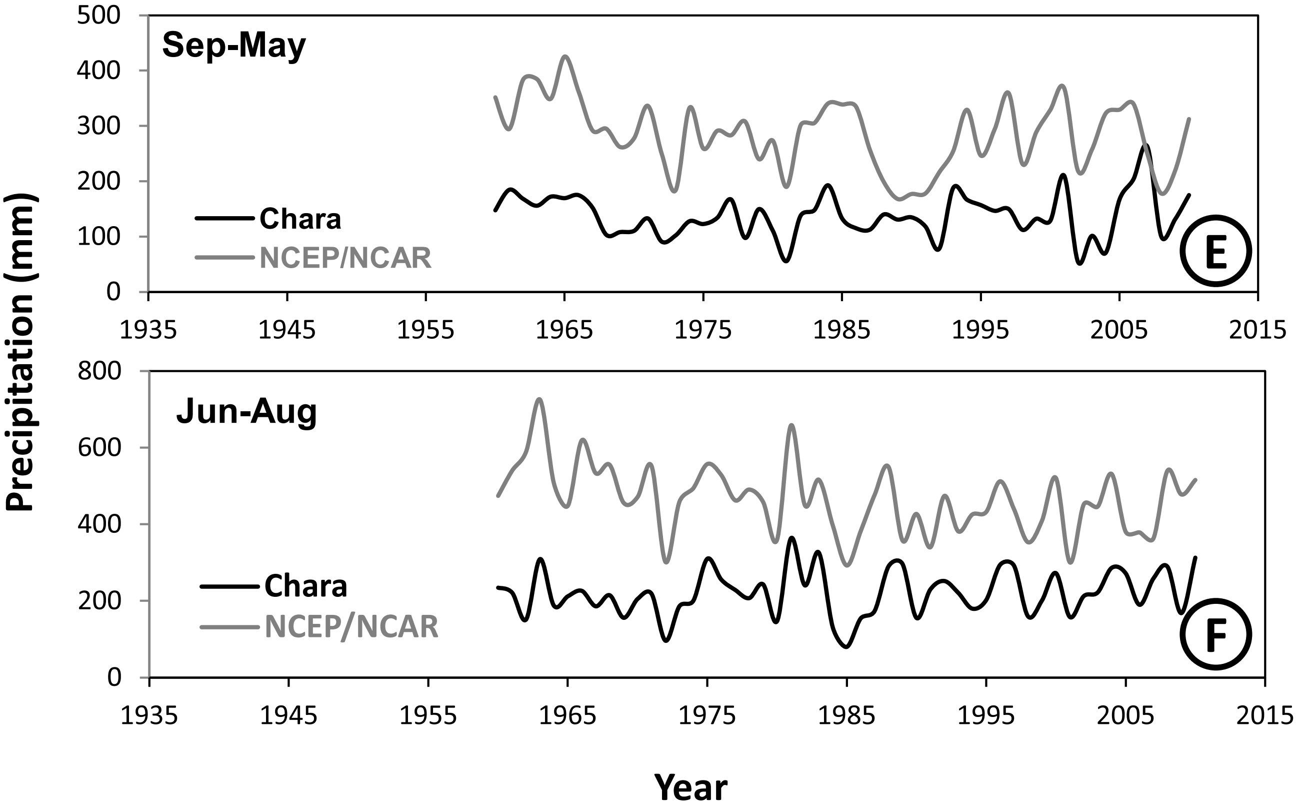
Total area of exposed ice (km²)
14
12
10
8
6
4
2
0
1960
1970
1980
1990
2000
2010
2020
Year


33
34
35
36
0
1
2
km

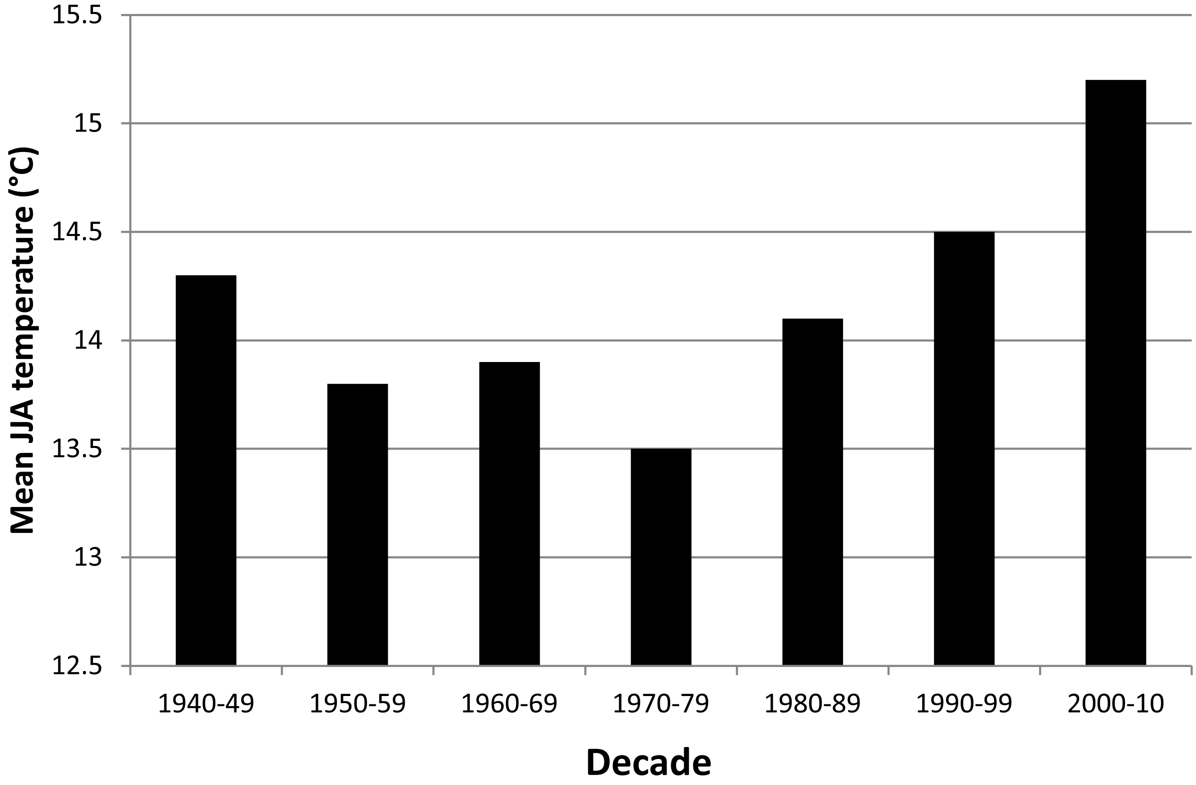

13
19
0
1
2
km


28
27
0
1
2
km


Jun-Aug
A
Sep-Nov
B
Mar-May
C
Dec-Feb
D
Temperature (°C)
Year
18
16
14
12
10
-4
-6
-8
-10
-12
-2
-4
-6
-8
-10
-23
-28
-33
-38
1935
1945
1955
1965
1975
1985
1995
2005
2015



Sep-May
Chara
NCEP/NCAR
E
Jun-Aug
Chara
NCEP/NCAR
F
Precipitation (mm)
Year
500
400
300
200
100
0
800
600
400
200
0
1935
1945
1955
1965
1975
1985
1995
2005
2015


15.5
15
14.5
14
13.5
13
12.5
Mean JJA temperature (°C)
1940-49
1950-59
1960-69
1970-79
1980-89
1990-99
2000-10
Decade