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Rapid glacial retreat on the Kamchatka Peninsula during the early 21st Century

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Abstract. Monitoring glacier fluctuations provides insights into changing glacial environments and recent climate change. The availability of satellite imagery offers the opportunity to view these changes for remote and inaccessible regions. Gaining an understanding of the ongoing changes in such regions is vital if a complete picture of glacial fluctuations globally is to be established. With this in mind, here we use satellite imagery (Landsat 7, 8 and ASTER) to conduct a multi-annual remote sensing survey of glacier fluctuations on the Kamchatka Peninsula (Eastern Russia) over the 2000–2014 period. Glacier margins were digitised manually, and reveal that in 2000, the peninsula was occupied by 676 glaciers, with a total exposed-ice area of 664.8 ± 23.9 km^2. By 2014, the number of glaciers had increased to 766 (reflecting the fragmentation of larger glaciers), but their surface area had decreased to 465.1 ± 15.7 km^2. This represents a ~ 30% decline in total glacier surface area between 2000 and 2014, and a notable acceleration in the rate of area-loss since the late 20th century. Analysis of possible controls indicates that these glacier fluctuations were likely governed by variations in climate (particularly rising summer temperatures), though the response of individual glaciers was modulated by other (non-climatic) factors, principally glacier size and local shading.

1 Introduction

Since glaciers are intrinsically linked to climate (Oerlemans et al., 1998), fluctuations in their dimensions are some of the best natural indicators of recent climate change (Lemke et al., 2007; Paul et al., 2009). In recent years, the improved quality and availability of satellite imagery has allowed fluctuations of glaciers in isolated and often inaccessible regions to be studied remotely (Gao and Liu, 2001; Raup et al., 2007). This can reveal key information concerning the changing local climate, and provide insights into specific controls on glacier behaviour (e.g., allowing the role of climatic and non-climatic forcing to be assessed) (Tennant et al., 2012; Stokes et al., 2013; Burns and Nolin, 2013). Given this utility, we use remote sensing methods to investigate recent (2000–2014) fluctuations in the surface area of exposed ice on the Kamchatka Peninsula (Eastern Russia), and consider possible climatic and non-climatic controls on this behaviour. The Kamchatka Peninsula is of particular interest because investigation of its recent glacial history has been limited (c.f., Khromova et al., 2014; Earl and Gardner, 2016), despite being the largest glacierised area in NE Asia (Solomina et al., 2007), and a region where glaciers, climate and active volcanoes currently interact (Barr and Solomina, 2014).

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2 Study Area

2.1 Topography

Located in Far Eastern Russia, the Kamchatka Peninsula occupies ~ 260,000 km^2. It extends approximately 1,250 km from the Koryak Highlands in the north to Cape Lopatka in the south, and separates the North Pacific Ocean to the east from the Sea of Okhotsk to the west (Fig. 1). The peninsula has been shaped by both volcanic and glacial forces (Braitseva et al., 1995, 1997; Ponomareva et al., 2007, 2013; Barr and Clark, 2012 a,b), and is dominated by three mountain ranges: the Sredinny Range, the Eastern Volcanic Plateau and the Vostocny Range (Fig. 1). Sandwiched between these ranges is the Central Kamchatka Depression, with relatively flat terrain punctuated by high volcanic peaks (> 4000 m above sea level; a.s.l.). The three principal mountain ranges are orientated North East to South West, reflecting the position, and eastward movement of the Kuril-Kamchatka subduction zone, which forms an offshore trench running almost parallel to the peninsula's eastern coastline (Bulin, 1978). This subduction zone is responsible for the 30 active, and ~ 300 inactive, volcanoes on the peninsula (Solomina et al., 2007).

2.2 Climate

Kamchatka lies between 50°N and 61°N, and 155°E and 163°E, and its proximity to the Pacific Ocean and Sea of Okhotsk results in a significantly milder climate than much of adjacent Siberia. Average summer temperatures range from 10°C to 15°C (Ivanov, 2002), whilst average winter temperatures range from -8°C to -10°C in the south east, and from -26°C to -28°C in the interior and north west, where cold temperatures are amplified by the effects of continentality and higher altitudes. A similar gradient is visible in the precipitation regime, with average annual values of ~ 1500–2000 mm in the south east and 400–600 mm in the North West. This gradient is partly a consequence of the mountain chains acting as orographic barriers, impeding and disrupting air-flow from the Pacific (Barr and Clark, 2011). During winter, cold, dry air is drawn from the Siberian High over central Siberia (Barr and Solomina, 2014). However, this is tempered by the development of a low pressure system over the Sea of Okhotsk, which sustains precipitation and elevates temperatures during winter (Velichko and Spasskaya, 2002). During summer, the Pacific High, to the southeast, brings warm-moist air masses across the peninsula. Precipitation peaks during autumn, aided by the delayed onset of the East Asian Monsoon (Velichko and Spasskaya, 2002).

2.3 Glaciers

At present, glaciers on the peninsula are found within the three principal mountain ranges, and on the high volcanic peaks of the Central Kamchatka Depression (see Fig. 1). The first attempts to estimate the extent of the region's glaciers were made as part of the 'Catalogue of Glaciers in the USSR' published between 1965 and 1982 (Khromova et al., 2014), based on observations from topographic maps and aerial imagery captured in the early 1950s, supplemented by field studies (Kotlyakov, 1980). In this survey, 405 glaciers were documented, with a total area of ~ 874 km^2. This was used as a basis for the USSR Glacier Inventory (UGI), and the dataset was subsequently incorporated within both the World Glacier Inventory (WGI) (WGMS, 1989) and Randolph Glacier Inventory (RGI) version 2 (Arendt et al., 2012). Subsequent estimates of the total number and surface area of glaciers on the peninsula tend to differ. For example, Muraviev (1999) reports 448 glaciers, with a total area of ~ 906 km^2, while Solomina et al. (2007) report 446 glaciers, with a total area of ~ 900 km^2. Most recently, Earl and Gardner (2016) conducted extensive mapping of glaciers in Northern Asia using automated remote sensing techniques, and documented 984 glaciers on Kamchatka, covering a total area of 770.3 km^2. This data was incorporated into the most recent version of the RGI (version 5, released in July 2015), (Arendt et al., 2015). However, it is of note that the Earl and Gardner (2016) dataset is based on a mosaic of satellite images from multiple years (2000, 2002, 2009, 2011, 2013), meaning their estimate does not reflect glacier extent at a single point in time (or during a single year).

3 Methods

3.1 Data sources

Changes in glacier extent (exposed ice) on the Kamchatka Peninsula between 2000 and 2014 were determined through visual analysis of multi-spectral Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images (see Table 1). Scenes were orthorectified to WGS 1984 Universal Transverse Mercator (UTM) Zone 57N, and were filtered to find those with minimal cloud- and snow-cover. To achieve this, images were restricted to those captured during the ablation season (for Kamchatka this occurs from late July to early September). In total, 14 Landsat 7 (ETM+) scenes and one ASTER image were used for 2000, with 14 Landsat 8 (OLI) scenes used for 2014 (see Table 1). The Landsat scenes have a spatial resolution of 28.5 m for all bands except panchromatic band 8 (15m) and Thermal Infrared Sensor (TIRS) band 6 (60m), whilst the ASTER image (bands 1–3) has a spatial resolution of 15m. To analyse glacier topography, elevation data was obtained from the SRTM Global 30m digital elevation model (DEM) (reflecting the surface topography of the glaciers in 2000).

3.2 Delineation of glacier margins

As highlighted by Paul et al. (2013), the identification and mapping of glaciers from satellite images can be conducted using semi-automated techniques (e.g. Paul and Andreassen, 2009; Kamp and Pan, 2015; Smith et al., 2015; Earl and Gardner, 2016) or through manual digitising (e.g. Debeer and Sharp, 2007; Stokes et al., 2013). In the present study, in order to establish the best method for mapping glaciers on Kamchatka, both semi-automated techniques and manual digitisation were trialled. The semi-automated techniques (specifically a RED/SWIR ratio and Normalised Difference Snow Index (NDSI)) produced rapid outputs and were easily applied across large regions, but had difficulty differentiating ice from the surrounding environment, often underestimating the exposed ice extent. The RED/SWIR band ratio had particular problems in distinguishing shaded areas and dirty ice, while the NDSI sometimes failed to distinguish ice from clouds and water bodies (see Fig. 2). Due to these difficulties, combined with the extensive manual editing and post-processing required to produce precise glacier margins, the semi-automated techniques were rejected in favour of manual mapping. Although time-consuming and sometimes subjective (Bhambri et al., 2011; Paul et al., 2013; Pfeffer et al., 2014), manual mapping remains the best method to extract detailed information on glacier dimensions (Kääb, 2005), whilst additionally allowing areas covered by shadow to be identified (see Fig. 2).

To help differentiate glaciers from their surroundings and aid in the visual detection of glacier margins, both true- and false-colour composites of the satellite images were generated (Malinverni et al., 2008), with the high resolution Band 8 (15m) used to sharpen the image. The true-colour composites were used for the identification of glaciers, while the false-colour composites helped differentiate ice and cloud, due to the strong absorption of ice in the SWIR band when compared to clouds (Nuimura et al., 2015). Glaciers were mapped in ArcGIS 10.2.2 (by a single operator) as polygon shapefiles, and features < 0.02 km^2 in 2000 were excluded from the analysis on the grounds that they are likely to be snow- or ice-patches, rather than glaciers (Paul and Andreassen, 2009; Bajracharya and Shresta, 2011; Frey et al., 2012; Racoviteanu et al., 2015). To help verify that each of the digitised polygons was an actual glacier rather than a transient snow-patch, scenes from intervening years, including 2015, were also obtained and analysed (Paul et al., 2009). However, the glacier inventory produced here does not contain detailed information about glacier dimensions for these intervening years since complete peninsula-wide imagery without extensive snow- or cloud-cover was unavailable for these periods, meaning that not all glaciers were mapped. For each of the glaciers mapped in 2000 and 2014, two-dimensional surface area was measured directly from the shapefiles, and area differences between 2000 and 2014 were calculated. Where glaciers fragmented into several distinct ice masses over this period, the net change in area was calculated based on the sum of the total area of each of the glacier ‘fragments’ (following Debeer and Sharp, 2007). For each glacier identified in the inventory in 2000, maximum, minimum and median altitude and mean surface slope were calculated from the SRTM DEM, and generalised glacier aspect was estimated from a line connecting the glacier’s maximum and minimum altitudes. The mean annual receipt of solar radiation at the surface of each glacier was calculated using the Solar Radiation tool in ArcGIS (algorithms developed by Fu and Rich, 2002), and glacier length was estimated along inferred flowlines.

3.3 Error Estimation

Potential sources of error in this study arise through the digitisation process and with difficulties in correctly identifying areas of exposed ice. The accuracy of digitisation depends partly on the spatial resolution of the satellite imagery, snow conditions and the contrast between glacier ice and the surrounding environment (Debeer and Sharp, 2007; Stokes et al., 2013). In Kamchatka, it is notable that the maritime conditions create particular difficulty with locating cloud-free imagery, and persistent snow-cover often hinders the clear identification of glacier margins (Paul and Andreassen, 2009). Where glacier margins were partially obscured by shadow, debris or cloud, careful analysis using multiple true- and false-colour composite

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band images, as well as thermal imagery, was undertaken to identify areas of ice with < 5 cm of debris cover (Ranzi et al., 2004; Nuimura et al., 2015). Error was calculated following the method described in Bajracharya et al. (2014):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(a_i - \hat{a}_i)^2}{n}} \quad (1)$$

where a_i denotes glacier area and $\hat{a}_i$ is the glacier area calculated on the pixel base (i.e., the total number of pixels within a polygon, multiplied by image resolution (15m)), and n is the number of polygons digitised. Error was found to be ~ 3.6% in 2000 and ~ 3.4% in 2014. These values are comparable to those reported in other studies (Bolch et al., 2010; Bhambri et al., 2013; Bajracharya et al., 2014).

3.4 Climate Data

NCEP/NCAR reanalysis data (see Kalnay et al., 1996), was used to analyse recent fluctuations in climate across Kamchatka. The NCEP reanalysis data integrates available land surface data from climate stations with the recovery of data from radiosondes, aircraft, ships and satellites to assimilate a quality controlled gridded (1.88° latitude x 1.88° longitude) record of surface climate variables for the period 1948 – present (Kalnay et al., 1996). Reanalysis data was used in preference to analysing individual weather stations, since the latter are often situated in coastal locations, distant from Kamchatka's glaciers. Additionally, many of the available station records include periods of missing data.

4 Results

4.1 Glacier inventory in 2000

In total, 676 glaciers, with a combined surface area of 664.8 ± 23.9 km^2, were identified and mapped on the peninsula in 2000 (see Fig. 1). Summary statistics for these glaciers are presented in Table 2, revealing a mean surface area of 0.98 km^2 (ranging from 0.02 to 22.99 km^2), with ~ 79% < 1 km^2, and less than 3% > 5 km^2, though the latter represent just over one third of the total glacier area. Glaciers range in length from 170 m to 9930 m, while ranging in altitude from 273 m to 4407 m (.a.s.l.), with a mean altitudinal range of 419 m, and a mean surface slope of 16.9°. The mean annual receipt of solar radiation at the surface of each glacier ranges from 57.5 to 169.5 (kWh/m^2).

4.2 Changes in glacier number and extent between 2000 and 2014

In 2014, 766 glaciers, covering an area of 465.1 ± 15.7 km^2, were identified and mapped on the peninsula. This represents an additional 90 glaciers, but an overall area loss of 199.6 ± 7.2 km^2 (~ 30%), relative to 2000 (Fig. 3A). The increase in glacier number occurred despite the complete disappearance of 42 glaciers during this period (these glaciers were all < 0.5 km^2 in 2000), and primarily reflects the fragmentation of larger glaciers. Of the peninsula's 676 glaciers identified in 2000, 659 (97%) experienced a reduction in surface area by 2014, and this decline is seen across the peninsula (Fig. 3A). Of the 17 glaciers that increased in area during this period, the majority experienced minor growth, though one glacier increased by ~ 140% (see Fig. 3B). In addition to areal decline, signs of stationary thinning (downwasting) are apparent in many areas, reflected by the exposure of many rock outcrops and the fragmentation of glaciers (see Fig. 4). The exposure of bedrock in this way further accelerates glacier wastage as local albedo is reduced (Paul et al., 2007).

4.3. Climate

When analysed across the peninsula, the NCEP data appear to indicate a reduction in precipitation between the 1970s and 1990s, but a precipitation increase thereafter (see Fig. 5A). This recent increase in precipitation is particularly notable during autumn (Fig. 5A). The temperature data (Fig. 5B) appears to show a warming trend from the 1950s to the late 1990s, which has continued (with some fluctuations) to the present day. Most significantly, there has been a sharp increase in average summer temperatures (June, July and August) since the early 21st century (see Fig. 5B).

4.4. Glacier attributes and glacier area change

Glacier size (area, perimeter, length and relief), altitude (including surface slope), and aspect (based on the glaciers mapped in 2000) were compared to absolute and relative changes in glacier surface area across the peninsula. These comparisons reveal a strong negative, and statistically significant ($p < 0.001$) correlation between the 2000 to 2014 change in glacier surface area (in km^2) and glacier area ($r = -0.76$), length ($r = -0.57$) and relief ($r = -0.51$) in 2000 (Fig. 6A-B). When change in area is expressed as a percentage of the original glacier size (rather than total area), these correlations become positive ($r = 0.21$, 0.27, and 0.24 for surface area, length and relief, respectively), and are weakened (though they remain statistically significant) (Fig. 6C-D). There is also a negative, and statistically significant, correlation between glacier surface area change (in km^2) and both maximum ($r = -0.39$) and median ($r = -0.29$) glacier altitude. Again, when area change is expressed as a percentage, these correlations become positive ($r = 0.15$ and 0.13 for maximum, and median, respectively), and are weakened (though they remain statistically significant). When glacier minimum altitude or surface slope are considered, there is no statistically significant relationship with glacier area loss (when expressed as total area, or as percentage change). Glaciers are predominantly found with an aspect-bias towards northerly and western directions (48.96%), but aspect doesn't show a statistically significant relationship with changes in glacier surface area (when expressed as total area, or as percentage change). Analysis of insolation patterns reveals a weak, but statistically significant, correlation ($r = 0.19$) with change in glacier surface area, but only when expressed in km^2, rather than as a percentage.

5 Discussion

5.1 Comparison with previous inventories

Based on the data presented in the Catalogue of Glaciers in the USSR (see Sect 2.3.), and the findings of the present study, there was a ~ 23.9% decline in exposed glacier surface area on the Kamchatka Peninsula between the 1950s (exact date unspecified) and 2000, and a further ~ 30% loss between 2000 and 2014. Assuming linear trends, this indicates an area-loss rate of ~ 0.55–0.67 % a^{-1} between 1950 and 2000, and a notable acceleration to ~ 2.52% a^{-1} since 2000. The reduction in glacier area during the late 20th century coincides with negative trends in glacier mass balance on the Peninsula (see Barr and Solomina, 2014). Unfortunately, since 2000, mass balance data have not been collected for Kamchatka's glaciers, and it is not possible to assess whether accelerated mass loss over the early 21st century has coincided with the accelerated glacier shrinkage identified here.

In terms of glacier surface area, it is notable that our estimate from 2014 (465.1 ± 48.8 km^2) differs significantly from Earl and Gardner's (2016) estimate (770.3 km^2). This we attribute to their semi-automated approach to mapping (i.e., NDSI), which can lead to an overestimation of glacier area as a result of snow patches being erroneously classified as glaciers (Man et al., 2014), combined with the fact that their inventory was generated from a composite of satellite images, meaning their mapping does not reflect glacier extent during a single specified year (as noted in Sect. 2.3.).

5.2 Potential climatic controls on glacier fluctuations

In the small number of studies to consider the issue, the retreat of Kamchatka's glaciers over recent decades has typically been attributed to variations in climate. For example, Yamaguchi et al. (2008) consider the retreat of Koryto glacier (54.846°N, 161.758°E) between 1711 and 2000 to be as a result of decreased precipitation over this period. Similarly, in the Northern Sredinny range, Muraviev and Nosenko (2013) note that from 1950 to 2002, average summer temperatures increased, while solid precipitation (snowfall) decreased, and suggest that this caused the retreat of the region's glaciers.

Based on climatic trends identified from the NCEP data, it might be argued that the loss of glacier surface area across Kamchatka between the 1950s and 2000 reflects the combined influence of rising temperatures and declining precipitation. However, since 2000, despite an increase in precipitation, glacier area loss has continued, and appears to have accelerated. This might reflect a delayed response to earlier, drier, conditions, but is also likely driven by a notable increase in temperatures since the mid-1990s. In particular, the pronounced rise in summer temperature (see Fig. 5C) is likely to have increased the intensity of melt, whilst rising autumn temperatures (Fig. 5B) may have lengthened the ablation season (simultaneously shortening the accumulation season). Therefore, it would appear that temperature has been the primary control on early 21st Century glacier fluctuations in Kamchatka, with rising temperatures driving a notable decline in glacier surface area, despite a corresponding rise in precipitation (even during winter).

5.3 Potential non-climatic controls on glacier fluctuations

Despite evidence for climatic control over glacier fluctuations in Kamchatka (outlined in Sect. 5.2.), the individual response of these glaciers is likely to have been modulated by other, local, non-climatic factors (Evans, 2006; Tennant et al., 2012; Stokes et al., 2013). These factors potentially include glacier size (area, perimeter, length and relief), altitude (including surface slope), and aspect (Huss, 2012; Fischer et al., 2015).

5.3.1 Glacier size

Comparisons between glacier size and surface area fluctuations suggest that smaller glaciers, though losing least surface area, actually lost a greater proportion of their total area. Similar trends, with small glaciers showing a propensity to shrink rapidly, have been found in numerous regions globally (see Ramírez et al., 2001; Granshaw and Fountain, 2006; Paul and Haeberli, 2008; Tennant et al., 2012 Stokes et al., 2013), and are considered to reflect the greater volume-to-area and perimeter-to-area ratios of smaller glaciers—meaning they respond rapidly to a given ablation rate (Granshaw and Fountain, 2006; Tennant et al., 2012). This rapid decline in the area of smaller glaciers on the Kamchatka Peninsula could result in the loss of many over coming decades, as ~ 78% of the glaciers mapped in 2014 have an area < 0.5 km^2. This supports the view of Ananicheva et al. (2010), who suggest that by 2100, only the largest glaciers on the highest volcanic peaks will remain.

5.3.2 Glacier altitude

Comparisons between glacier median and maximum altitude and surface area fluctuations would appear to suggest that these factors exert some control on area change, however, the lack if any statistically significant relationship between area loss and minimum altitude might indicate that, rather than exerting a direct control on glacier area, glaciers with high maximum and median altitudes are typically the largest on the peninsula (i.e., there are positive and statistically significant relationships between glacier area and both maximum (r = 0.38) and median (r = 0.29) altitude), and that size exerts the primary control on glacier behaviour in this relationship.

5.3.3 Glacier aspect

The aspect bias exhibited by Kamchatkan glaciers, combined with the statistically significant relationship between area loss and total insolation indicates that glaciers exposed to most solar radiation typically show a greater reduction in their overall surface area, (see Evans, 2006). However, the lack of a statistically significant relationship between glacier aspect and changes in glacier surface area, suggest that local variations in insolation (e.g., related to topographic shading) are likely important in protecting glaciers from recession (see Paul and Haeberli, 2008). Note, the lack of any clear aspect control on glacier fluctuations has also been observed in other regions globally (Debeer and Sharp, 2007; Tennant et al., 2012), and is often considered to reflect the importance of other factors (e.g., local shading, debris cover, etc.) in modulating glacier recession (Stokes et al., 2013).

5.3.4 Other non-climatic factors

Across the peninsula, 165 glaciers are located within a 50 km radius of an active volcano, with 292 glaciers within a 100 km radius. Although, there is evidence that some of these glaciers were covered by tephra as a result of proximal volcanic activity, there is no evidence to suggest that this had a discernible influence of glacier fluctuations during the period of observation. In addition, due to their volcanic setting, some of Kamchatka's glaciers are known to be of 'surge-type' (Vinogradov et al., 1985;

Yamaguchi et al., 2007). However, there was no evidence of surge activity during the period of observation, perhaps reflecting the comparatively short time period considered.

6 Conclusion

In this paper, manual digitisation from satellite imagery is used to map the area of exposed ice for all glaciers on the Kamchatka Peninsula in 2000 and 2014. This is the first study to consider peninsula-wide patterns in glacier behaviour over the early 21st Century, and variations in glacier extent are put in context through comparison with published glacier extent estimates from the 1950s (Kotlyakov, 1980). The main study findings can be summarised as follows:

1. In total, 676 glaciers, with a combined surface area of 664.8 ± 23.9 km^2, were identified and mapped on the peninsula in 2000. By 2014, the total number of glaciers had increased to 766 but their surface area had reduced to 465.1 ± 15.7 km^2 , this suggests a notable acceleration in the rate of area loss (from ~ 0.55–0.67 % a^{-1} to ~ 2.52% a^{-1}) since 2000. The increase in glacier number, despite the complete disappearance of 42, is considered to reflect the fragmentation of larger glaciers during this period.
2. Based on the analysis of NCEP/NCAR reanalysis climate data, it appears that the reduction in glacier surface area on the peninsula between the 1950s and 2000 likely reflects the combined influence of rising temperatures, and declining precipitation. However, accelerated area loss since 2000, despite increased precipitation, is likely a response to a notable increase in temperatures across the peninsula since the 1990s. Specifically, the rise in summer temperatures is likely to have enhanced the intensity of melt, whilst rising autumn temperatures may have lengthened the ablation season, simultaneously shortening the accumulation season.
3. Despite the overall climatic control there is evidence that the behaviour of individual glaciers on the peninsula is modulated by local, non-climatic factors. Specifically, smaller glaciers, though losing least absolute surface area, lost a greater proportion of their total area. This propensity to shrink rapidly is considered to reflect the greater volume-to-area and perimeter-to-area ratios of smaller glaciers, meaning that they have a heightened sensitivity to changing climate (see Granshaw and Fountain, 2006). Though glacier altitude shows some relation with area change, this probably reflects the positive relationship between glacier altitude and size (rather than an altitudinal control on glacier behaviour). Insolation patterns show a weak, but statistically significant, relationship with changing glacier surface area, indicating that glaciers exposed to most solar radiation experienced a greater reduction in their overall surface area. However, glacier aspect fails to show a statistically significant relationship with changes in glacier surface area, suggesting that local variations in insolation (e.g., related to topographic shading) are important in regulating fluctuations of Kamchatka's glaciers.
4. If the rapid decline in the surface area of smaller glaciers on the Kamchatka Peninsula continues over the 21st Century, many will be lost by 2100 (Ananicheva et al., 2010), since ~ 78% of the region's glaciers identified in 2014 have an area < 0.5 km^2.

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Table 1. Satellite images used to generate the glacier inventory

2000			2014		
Path	Row	Date	Path	Row	Date
98	21	22/09/2000	97	22	29/08/2014
98	22	22/09/2000	98	19	05/09/2014
98	22	06/09/2000	99	19	27/08/2014
98	23	06/09/2000	99	20	27/08/2014
99	18	28/08/2000	99	21	27/08/2014
99	22	28/08/2000	99	21	12/09/2014
99	23	28/08/2000	99	22	12/09/2014
100	19	18/07/2000	99	23	27/08/2014
100	20	19/08/2000	99	23	12/09/2014
100	21	19/08/2000	99	24	12/09/2014
100	22	19/08/2000	100	19	19/09/2014
100	23	20/09/2000	100	20	19/09/2014
100	24	20/09/2000	101	21	10/09/2014
ASTER		20/07/2000	101	22	10/09/2014

Table 2. Statistics for glaciers on the Kamckatka Peninula in 2000 (topographic attributes are derived from the SRTM 30m DEM).

	Min	Mean	Max
Area (km^2)	0.02	0.98	22.99
Minimum Altitude (m.a.s.l)	273	1300	2899
Median altitude (m.a.s.l.)	544	1504	3559
Maximum altitude (m.a.s.l.)	577	1719	4407
Altitudinal range (m)	17	419	2142
Maximum flowline length (m)	170	1545	9930
Mean surface slope (°)	5.7	16.9	35.5
Mean annual solar radiation (kWh/m^2).	57.5	111.9	169.5

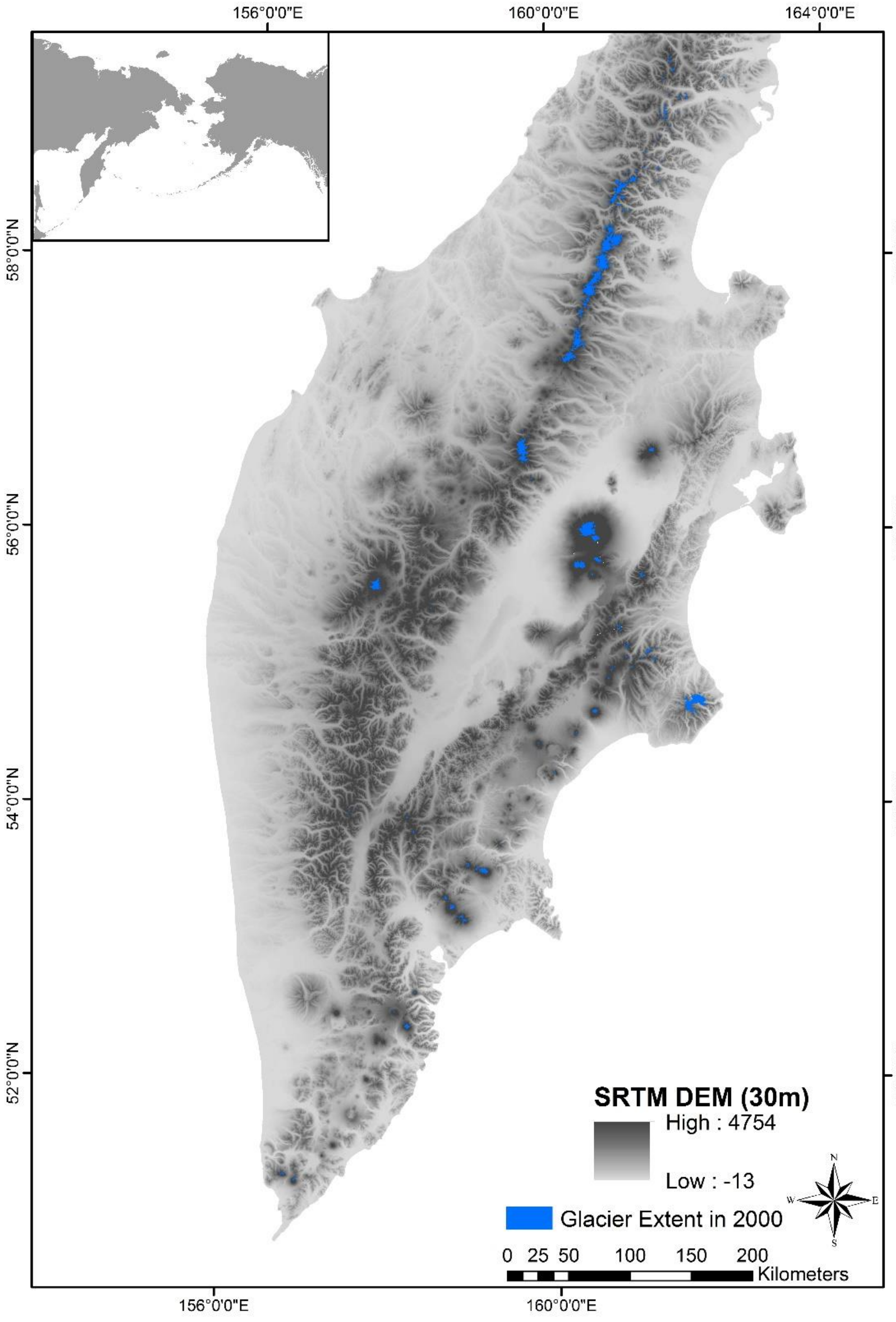

Figure 1: Map of the Kamchatka Peninsula (Russia) with glacier extent in 2000 shown in blue.

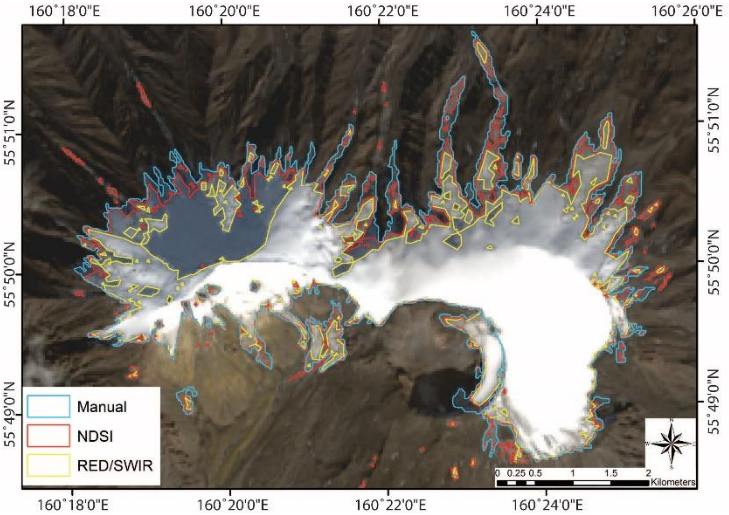

Figure 2: Comparison of glacier margins delineated by two semi-automated techniques and manual mapping.

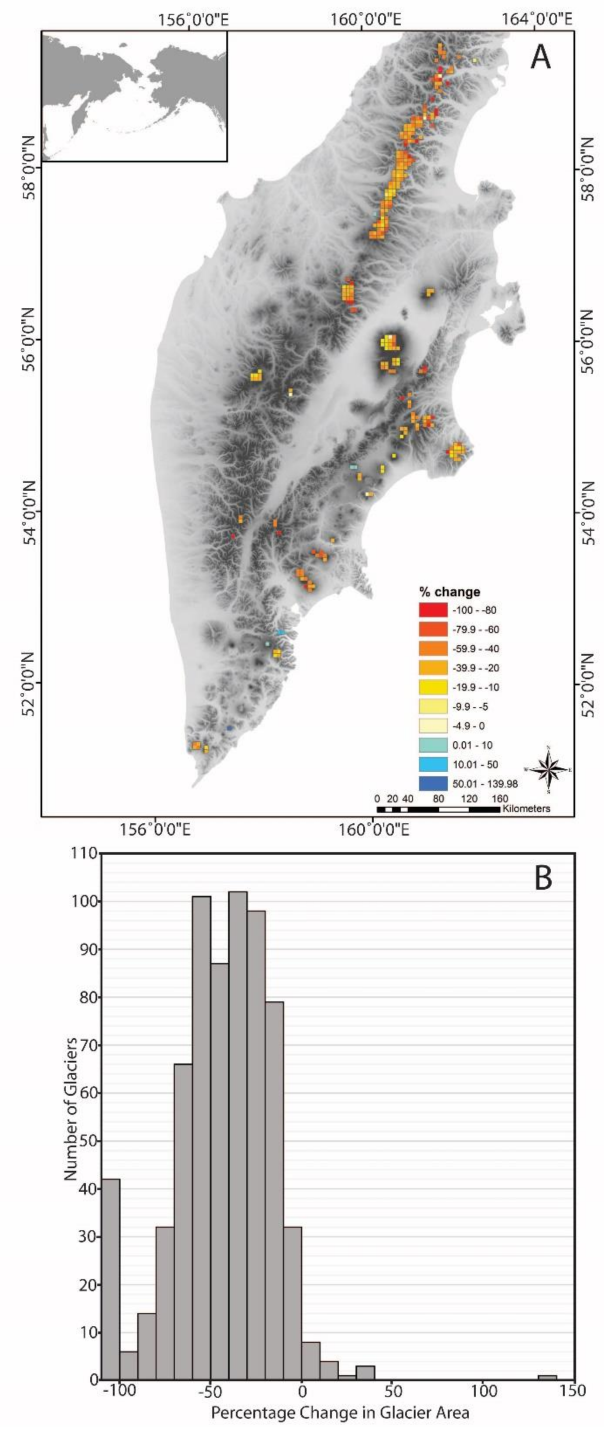

Figure 3: Percentage change in glacier surface area across the Kamchatka Peninsula between 2000 and 2014. (A) Mean values shown for 5 x 5 km grid cells. (B) Values for individual glaciers shown as a frequency distribution.

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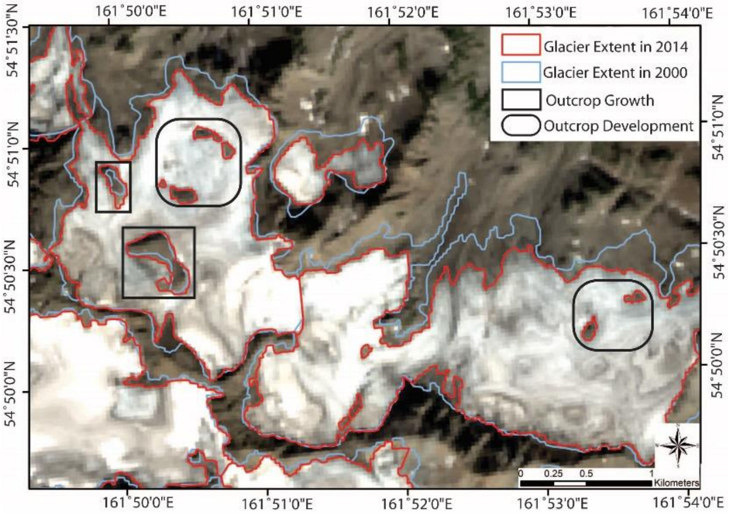

Figure 4: Examples of glaciers on the Kronotsky Peninsula mapped extent in 2000 and 2014 (Landsat 2014 background image), revealing stationary thinning and a notable decline in glacier surface area.

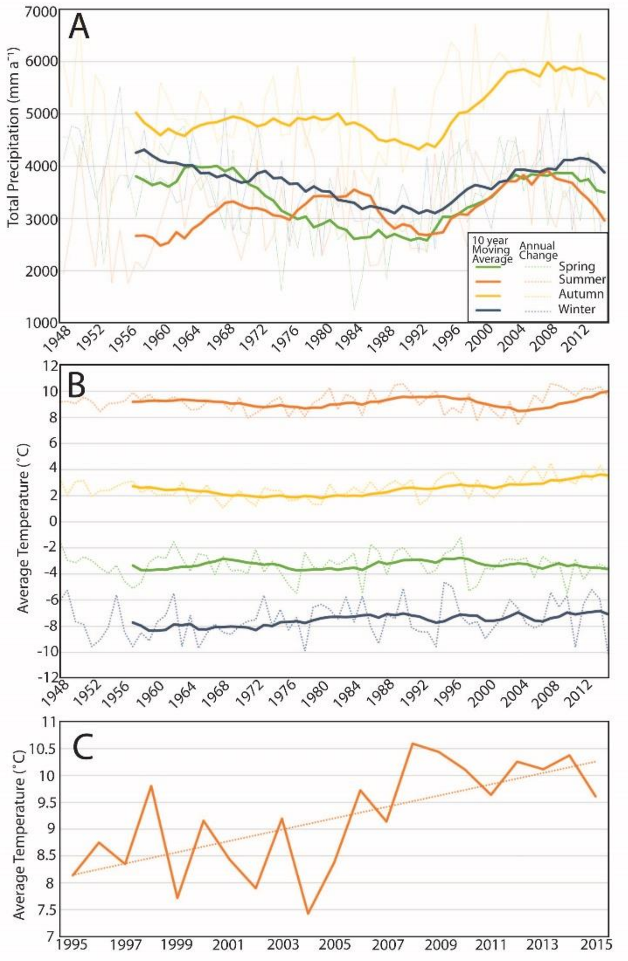

Figure 5: Climatic Variation on the Kamchatka Peninsula between 1948 and 2015, derived from NCEP/NCAR reanalysis figures averaged across the whole peninsula (see Kalnay at al., 1996). (A). Seasonal precipitation record. (B). Average seasonal temperature. (C). Summer temperature record from 1995-2015.

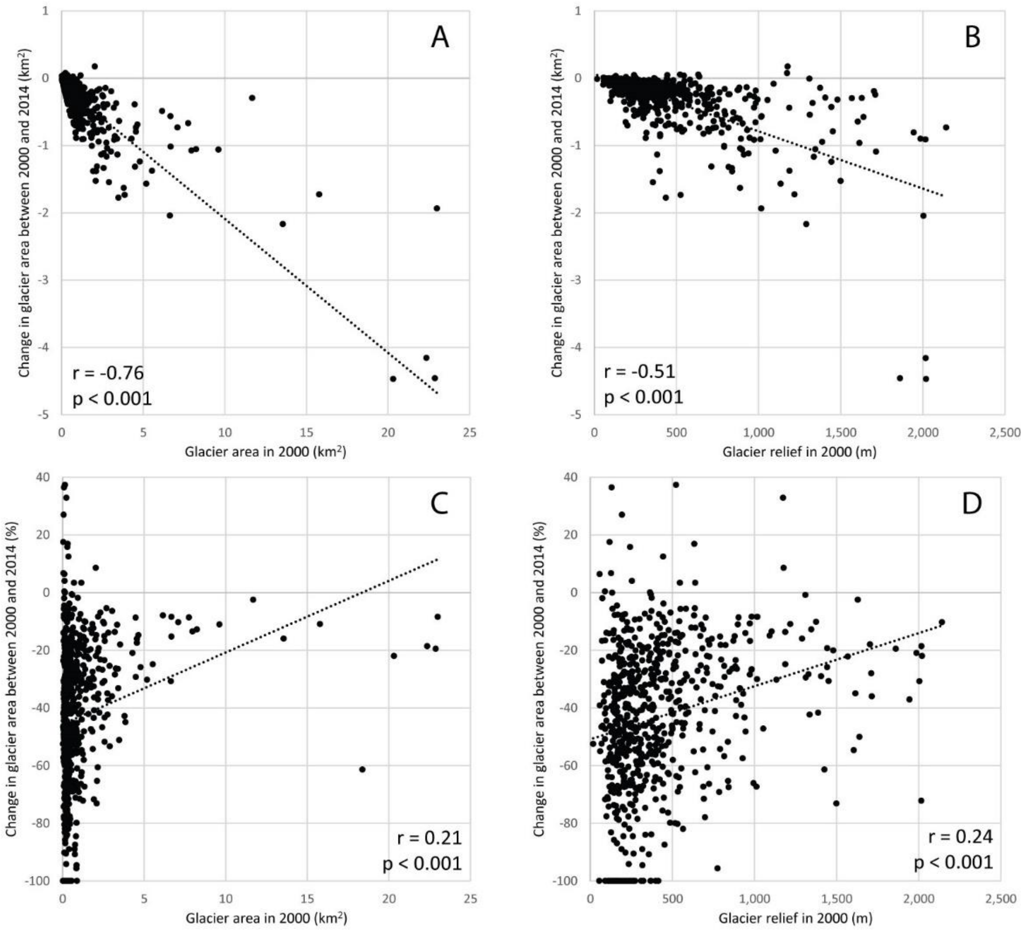

Figure 6: Relationships between glacier area changes from 2000 to 2014 (in km^2) and glacier (A) surface area, and (B) relief. These same relationships, but with percentage area loss are plotted in (C) and (D).